AD NUMBER	
AD385891	
CLASSIFICATION CHANGES	
TO:	unclassified
FROM:	confidential
LIMITATION CHANGES	
TO:	Approved for public release, distribution unlimited
FROM:	Distribution authorized to DoD only; Test and Evaluation; AUG 1967. Other requests shall be referred to Army Aviation Materiel Laboratories, Fort Eustis, VA 23604.
AUTHORITY	
USAAMRDL notice dtd 27 Oct 1971; USAAMRDL ltr dtd 30 Mar 1976	

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USAAVLABS TECHNICAL REPORT 67-42

INVESTIGATION OF LANDING GEAR FLOTATION CRITERIA FOR THE HEAVY LIFT HELICOPTER (U)

By

D. Harding

August 1967

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

CONTRACT DA 44-177-AMC-455(T)
VERTOL DIVISION
THE BOEING COMPANY
MORTON, PENNSYLVANIA

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(U) The work reported herein was conducted by The Boeing Company, Vertol Division. This command concurs in general with the information presented in the report. The results of this effort are expected to be of value in the design of landing gears for large helicopters.

(U) This report is published for the dissemination of information and the stimulation of ideas.

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Task 1F121401A14184
Contract DA 44-177-AMC-455 (T)
USAAVLABS Technical Report 67-42
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Prepared by
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for

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(U) SUMMARY

Missions analyses were performed for a draft QMR-type Heavy Lift Helicopter operating in Southeast Asia, Western Europe, and Continental United States theaters in order to establish landing gear requirements. The results of these analyses indicate that the Heavy Lift Helicopter (HLH) is concerned primarily with performing a large variety of tasks and, with the possible exception of ship-to-shore unloading, there are no highly repetitive missions. The vast majority of cargo will be carried as an external sling load acquired and released from a hover attitude; landing requirements are minimal, and ground maneuvering in unsurfaced soil is not required. Both crane and transport configurations are equally capable for the majority of missions from landing gear flotation considerations; however, the helicopter configured solely for external loads has an advantage, since tire pressures may be reduced to correspond to the basic weight condition.

Due to the expected utility of the HLH, sufficient landing gear flotation must be provided to allow landings without damage to all Zone of Interior (ZI) airfields and most roads and parking lots. Flotation criteria for operation from Theater of Operations (TO) airfields require the establishment of the number of coverages allowed the aircraft before pavement or surface failure occurs. Missions analyses indicate that the number of operations which may be expected of the HLH from TO fields is limited; however, it was not possible to establish an actual value since it is necessary to consider the other aircraft that use the field, and also because it was felt that the pass-to-coverage factors established for fixed-wing aircraft did not represent helicopter operation and were therefore conservative.

The coverage rates recommended by the Corps of Engineers were used in the flotation analysis to indicate corresponding landing gear requirements.

Operations from unprepared terrain were divided into two classes: those in which the minimum landing area soil strength was defined by the characteristics of the mission, such as the ability of a truck to operate, and those in which soil strengths are random, such as recovery of a downed aircraft. Missions of the latter type represented 1 percent in only one theater considered.

The flotation criterion selected for operation in unprepared terrain was a wheel sinkage limit of one-third of the diameter (D/3). The sinkage analysis was made by using the Army Tank Automotive Center methods, and results were examined for three soft soils with Cone Indexes of 60, 30, and 10. The effects of these various flotation criteria on landing gear weight and aircraft performance were determined for a variety of gear configurations.

Sinkage in Cone Index 60 soil was the least critical of the criteria examined. The criteria derived from sinkage in Cone Index 30 soil and from Theater of Operations support- and forward-area airfields all produced similar results; together these criteria represent the vast majority of missions. Flotation in Cone Index 10 soil applies in approximately 0.03 percent of missions and results in a weight penalty of 1.1 percent for the crane configuration and 2.0 percent for the transport configuration, with wheel-type landing gear in each case. With the removable ski-type gear, the penalty is approximately 0.65 percent for the crane configuration and 1.0 percent for the transport configuration.

(U) CONTENTS

(U) ILLUSTRATIONS

(U) TABLES

(C) INTRODUCTION (U)

(U) Considerable effort has been expended in recent years to define more thoroughly the landing gear properties or degree of flotation required to permit operation of an aircraft from a particular airfield. The Unit Construction Index (UCI) method has been replaced by more definitive methods for Zone of Interior and Theater of Operations airfields. These methods allow the procuring agency to define the flotation requirements in terms of the expected operation of the aircraft.

(C) The suggested landing gear flotation criterion for the Heavy Lift Helicopter, as contained in the draft Qualitative Materiel Design Objective (QMDO), was a requirement for one pass in CBR-1.5 soil. Preliminary design studies performed by the Vertol Division of Boeing indicated that:

1. This criterion did not seem to truly represent the intended use of the helicopter.

2. Small changes in the flotation requirement produced disproportionately large changes in landing gear weight.

3. Specification of flotation criteria for soft-soil conditions did not necessarily guarantee successful operation from prepared surfaces.

(U) Furthermore, since an aircraft of the size and class of the Heavy Lift Helicopter has not been used under combat conditions, more realistic criteria could not be established on the basis of experience.

(U) Realization of this position led the U. S. Army Aviation Materiel Laboratories to issue RFQ AMC(T) 44-177-66 (Neg 102) for a program for investigation of landing gear flotation criteria for the Heavy Lift Helicopter. Subsequently, a contract was received by the Vertol Division of Boeing to perform this work. The objective of the study, which is described in this report, was to select the landing gear flotation criteria by performing a mission analysis for a Heavy Lift Helicopter, as defined by the draft Qualitative Materiel Requirement, and then evaluating tradeoffs between flotation and weight and performance.

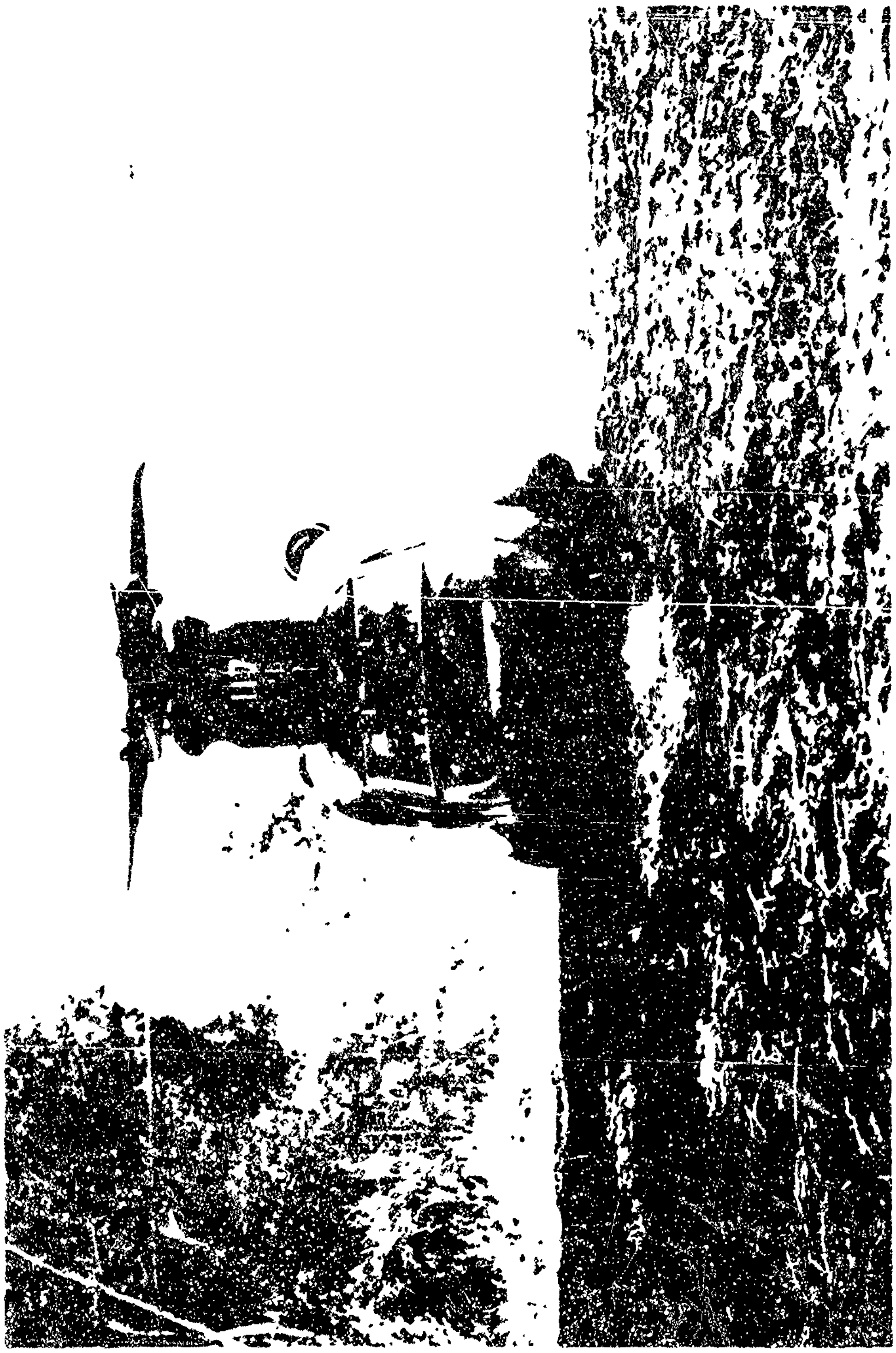


FIGURE 1. (U) CH-47A CHINOOK LANDING IN SOFT UNPREPARED SOIL DURING TESTS PERFORMED BY U.S. ARMY WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS, VICKSBURG, MISSISSIPPI

(U) LANDING GEAR FLOTATION

The degree of landing gear flotation built into an aircraft, as specified by the procuring agency, is dependent on that aircraft's intended utilization. The flotation criteria are selected so that the aircraft is able to complete a specified number of missions from a given airfield before the surface becomes unusable due to rutting or cracking. Also, if the aircraft is required to operate from unprepared soft soil, the flotation criteria will indicate the strength of soil from which operations must be made.

Military airfields are designed and constructed by the Army Corps of Engineers. The airfields are divided into two categories as described in Ground Flotation Requirements for Aircraft Landing Gear (Reference 6) published by U. S. Army Corps of Engineers, Waterways Experimental Station (WES), Vicksburg, Mississippi. These are:

1. Zone of Interior (ZI)
2. Theater of Operations (TO)

ZONE OF INTERIOR AIRFIELDS

Zone of Interior airfields are permanent facilities and are classed as having heavy-, medium- or light-load pavement. The two former are of concrete construction while the latter may be of either concrete or bituminous construction. Zone of Interior airfields are defined as follows:

1. Heavy-Load Airfield - An airfield that must support heavy-bomber-type aircraft. The load-carrying capacity of pavement for this type of airfield is equivalent to a main gear load of 265,000 pounds for a four-wheel twin-twin configuration having tire contact areas of 267 square inches for each wheel, twin spacing of 37 inches center-to-center, and inside wheels of twins spaced at 62 inches center-to-center.

2. Medium-Load Airfield - An airfield that must support heavy cargo, tanker, and medium bomber aircraft. The load-carrying capacity of pavements for this type of airfield is equivalent to a main gear load of 100,000 pounds on a two-wheel, twin configuration having tire contact areas of 267 square inches for

each wheel and wheel spacing of 37 inches center-to-center.

3. Light-Load Airfield - An airfield that must support fighter- and medium-cargo-type aircraft. The load-carrying capacity of pavements for this type of airfield is equivalent to a main gear load of 25,000 pounds on a single wheel having a tire contact area of 100 square inches.

As already noted, ZI pavements are of either rigid (concrete) or flexible (bituminous) construction or a combination of the two. Concrete pavements are termed rigid since they behave like thick metal plates on a rubber foundation. The design conditions for a concrete pavement are concerned with the maximum stress created in the concrete by the landing gear; the pavement is not susceptible to cumulative fatigue damage. Analysis of these stresses is quite complex, particularly for aircraft having multiple-wheel landing gear. However, since the pavements of military airfields are of a standard construction, it was possible to develop a set of design curves relating to gear load, tire spacing and tire footprint area. These curves and a description of their use are contained in References 6 and 7.

It is interesting to note that tire pressures below about 350 psi do not have significant effect on the pavement stresses, except that they tend to increase the bending moments due to the concentrated loading.

Since the mass of a concrete pavement is enormous when compared to that of the aircraft, the loads experienced by the pavement on landing impact do not represent increased pavement stress; flotation criteria are actually based on the standing load on the landing gear.

The design pavement life is 10 years; however, in special circumstances an overload condition may be tolerated at the expense of surface cracking and reduced life. Responsibility for rigid pavement design lies with the U.S. Army Corps of Engineers, Ohio River Division, Cincinnati, Ohio.

THEATER OF OPERATIONS AIRFIELDS

Theater of Operations airfields (more specifically TO airfield types) are limited-life facilities which represent the maximum

construction capability of engineer troops in the field, considering time limitations imposed by the tactical situations and available construction equipment and surfacing materials. Design and evaluation of TO airfields are the responsibility of the U. S. Army Corps of Engineers, Waterways Experimental Station (WES), Vicksburg, Mississippi. The TO airfield classes are defined as follows:

1. Rear-Area Airfields - Airfields that normally must support the operation of heavy cargo aircraft, medium cargo aircraft, and fighter-bomber aircraft for a period of four to six months. Airfields of this class will be constructed, rehabilitated, extended, and maintained by engineer construction battalions and will usually be located in the Zone of Communications or in the Army rear area. The strength characteristics of the rear-area airfield will normally govern the landing gear flotation design for heavy cargo and fighter-bomber aircraft. The controlling rear-area airfield is characterized as a field having the equivalent of a T11 landing mat surface lying directly on a 4-CBR subgrade.

2. Support-Area Airfields - Airfields that normally must support the operation of medium cargo aircraft (and conceivably, certain fighter-bomber aircraft designed for close tactical support) for a period of from two weeks to one month. Airfields of this class may be constructed by several types of engineer units including engineer construction battalions, engineer combat battalions and light equipment companies, and will usually be located in the Corps forward area or Division rear area. The strength characteristics of the support-area airfield will normally govern the landing gear flotation design for medium cargo aircraft with such typical missions as the bulk delivery of supplies to Corps and Division forces in an intratheater air line of communications. The controlling support-area airfield is characterized as a field having the equivalent of an M8 landing mat surface lying directly on a 4-CBR subgrade.

3. Forward-Area Airfields - Airfields that must support the operation of liaison, observation, and light transport aircraft, including heavy cargo helicopters, for a period ranging from a few days to three weeks.

Airfields of this class will be constructed by engineer combat and airborne battalions, and usually will be located in the Division area of a combat zone. The strength characteristics of the forward-area airfield will normally govern the landing gear flotation design for any fixed-wing aircraft or heavy cargo helicopter with a mission requirement to operate in a near-frontline unit (for example, the retail delivery mission in an air line of communications). The controlling forward-area airfield is characterized as a field having a 4-CBR subgrade with no structural surfacing. It should be noted that an aircraft having sufficient flotation to operate on a 4-CBR subgrade for the design number of operations will have the capability of operating a lesser number of times on subgrade strengths substantially below 4-CBR.

4. Light VTOL Landing Areas - These are special-category landing areas which will normally require no construction effort other than the clearing of vegetation. They will be characterized as areas having an unsurfaced, 1-1/2-CBR subgrade; this will permit one to three operations of aircraft such as personnel transport helicopters on ground which, while having the minimum strength required for operation of most common military wheeled ground vehicles, can support these vehicles without significant danger of immobilization. It should be noted that the type of aircraft using this landing area will be capable of repeated operation from areas having greater (than 1-1/2-CBR) strength.

The mat-surfaced pavements of rear-area and support-area airfields are termed flexible pavements. This is because the function of the pavement or mat is to distribute the load to soil in such a way that shear failure of the soil does not occur. Unlike the rigid pavement, the flexible pavement does not have a fixed strength level in terms of pavement stress; instead it is subjected to cumulative fatigue damage from each load application. The failure criteria are when the surface has received sufficient damage to cause permanent surface rutting. The formula used to define the Index of Required Surface Strength (I_R) is a variation of that used in flexible pavement thickness determination and is useful in evaluating the capabilities of various landing gears on rear-area and support-area airfields.

The formula is:

$$I_R = (0.23 \log C + 0.15) \sqrt{\frac{P}{8.1\ CBR} - \frac{A}{\pi}} \qquad (1)$$

where:

A = contact area (in square inches) of one tire. This value can be determined by dividing the actual load in pounds on one tire by the tire pressure in pounds per square inch.

C = load repetition factor representing the level of load or stress repetitions which can be sustained.

CBR = measure of soil strength.

P = load per tire in pounds. This value for a multiple-wheel assembly is the actual load per tire if the center-to-center spacing of all tires is greater than four equivalent radii. However, if the center-to-center spacing of adjacent tires is less than four radii, the load per tire must be increased according to the requirements specified in Reference 6.

Each class of airfield for Theater of Operations use has a specific pattern of strength versus depth. This strength is expressed as the Index of Available Surface Strength (I_A); curves of I_A for rear and support-area fields are included in References 6 and 7. Comparisons of I_A and I_R for a specific landing gear configuration enable the designer to predict the number of coverages or the load repetition factor that may be achieved.

Landing gear flotation on a Theater of Operations forward-area field (unsurfaced soil CBR-4) is defined by the number of coverages or the load repetition factor necessary to cause permanent surface rutting (approximately 3 inches in clay and 4 inches in sand). In this instance landing gear flotation criteria are related only to surface damage. These criteria are based on adequate description of soil strength.

In road and airfield design, the commonly used definition of soil strength is the California Bearing Ratio (CBR). The CBR measure was developed by the California Department of Highways in 1927-1928 in order to improve the description of

soil behavior in road foundations. Soil CBR is determined by a laboratory test which consists of compaction of the soil in a mold for a period of four days, followed by a load bearing test which is performed by loading a 3-square-inch piston. A plot of the load displacement curve is compared to a standard 100-percent curve which represents the load bearing capacity of high-quality base course materials (crushed rock). The sample soil CBR is then defined as the percentage of the standard strength. Typical curves are shown in Figure 2.

Evaluation of flotation on unsurfaced airstrips is made by using a nomograph as shown in Figure 3. This nomograph, which is based on empirical data developed by WES, is the version which appears in References 6 and 7. Further tests since the release of those data indicate that the curve is unduly conservative; an improved version (WES No. 042666A) has been constructed and is in the process of review prior to substitution for the published curve. The revised nomograph was used for evaluation of flotation in this study.

In order to define the flotation required in an aircraft to perform a given mission from TO airfields, it is necessary to establish the number of operations required. If a mix of aircraft is contemplated, then the number of operations for each aircraft type must be specified, together with the fraction of pavement life allotted to that aircraft; e.g., the missions analysis may indicate that on a given airfield only 10 landings in 1000 will be made by the subject aircraft. However, this does not mean that 10 landings are to be used to define the number required of that aircraft. This is because, if the figure of 10 landings were used in the flotation analysis, the result would be a landing gear which would cause the pavement to fail in 10 landings. Therefore, the expected number of operations and the corresponding portion of total runway life must be used to generate an equivalent number of passes which can then be used to determine the failure point of the pavement.

This condition makes it mandatory for the mission analysis, in determining the required number of passes for a given airfield, to take account of the total aircraft operations in that theater.

However, the Corps of Engineers suggests that when the expected traffic cannot be adequately defined in cycles of operation, the traffic should be stated in terms of the load repetition

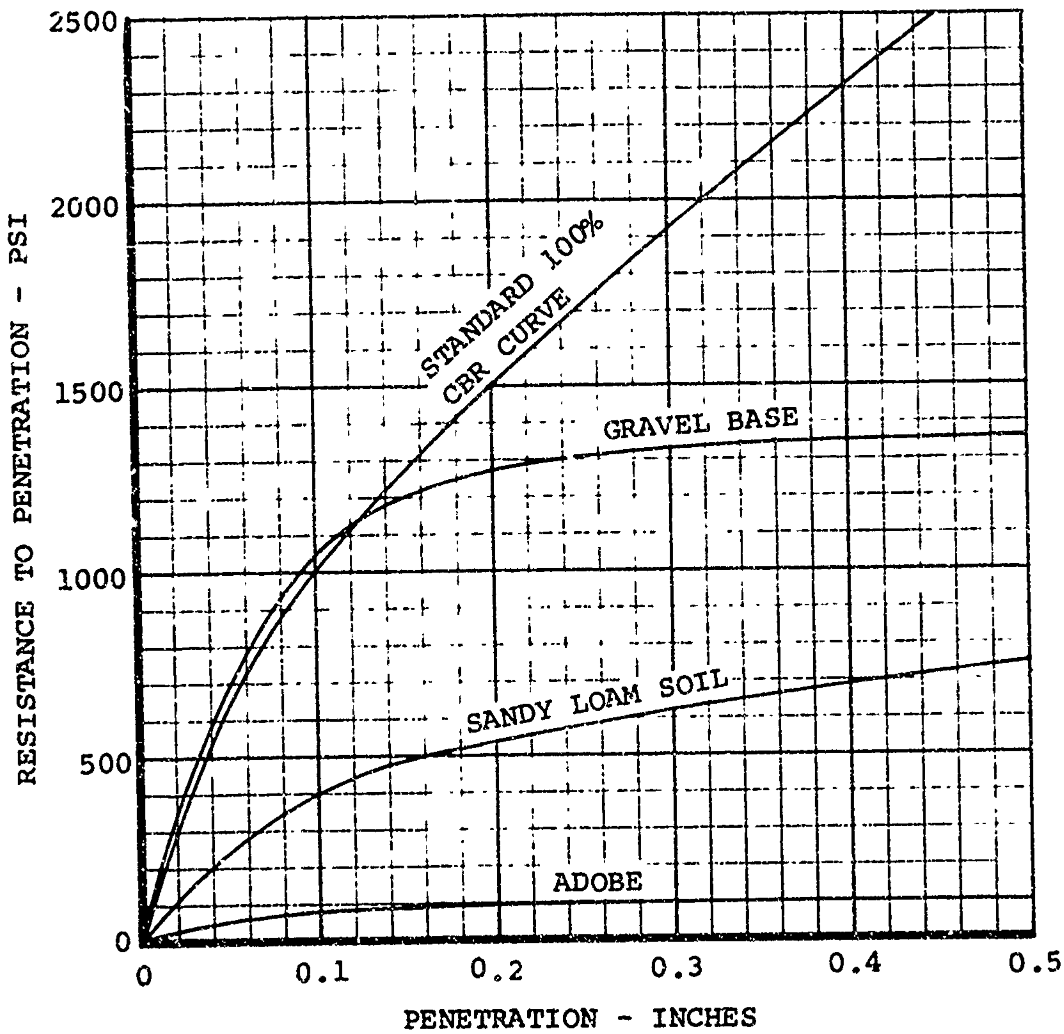


FIGURE 2. TYPICAL CBR CURVES

factor as follows:

TO Airfield Class	Load Repetition Factor
Rear area	1000
Support area	200
Forward area	40

To evaluate the capability of a landing gear when the traffic is stated in cycles of operation, it is necessary to convert this traffic from cycles of operation to a load repetition factor (C).

A cycle of operation is one takeoff and one landing, and a cycle applies one pass to the airfield system. An increment of the load repetition factor is the application of a sufficient number of passes to load every point within a given traffic lane once. Methods for evaluating the pass-to-coverage ratio are described in References 6 and 7. When considering helicopter operations, the concept and interpretation of pass-to-coverage ratio are extremely important. The application to fixed-wing aircraft is straightforward, since the operations are by their nature constrained to follow the path of the airstrip, and the number of passes to obtain one coverage is, therefore, easily defined. In the case of the helicopter, however, the operations may not be channeled into one specific lane, unless running takeoffs and landings are made on high-gross-weight missions, flown with internal cargo or rigidly-fixed podded loads. It can be argued, therefore, that even though the landing area may be significantly smaller than that required for a fixed-wing aircraft, the pass-to-coverage ratio may be significantly higher than that obtained by the methods currently used.

UNPREPARED TERRAIN

The foregoing flotation requirements are all concerned with damage done by the aircraft to a prepared runway surface. However, the helicopter, because of its inherent flexibility, frequently operates from unprepared terrain and, in these circumstances, the damage inflicted to the soil is not usually a consideration. Helicopters have been operated on soils so soft as to allow the landing gear to sink beneath the surface and cause the helicopter to rest on its belly. The requirements for operation under these conditions are that the helicopter must be able to pull itself out safely. Further, if

the helicopter is required to taxi in order to acquire a load or to make a running takeoff, then motion resistance becomes a consideration. The initial requirement, then, to permit specification of helicopter flotation in soft unprepared soil is a description of the soil strength anticipated for the helicopter's basic mission.

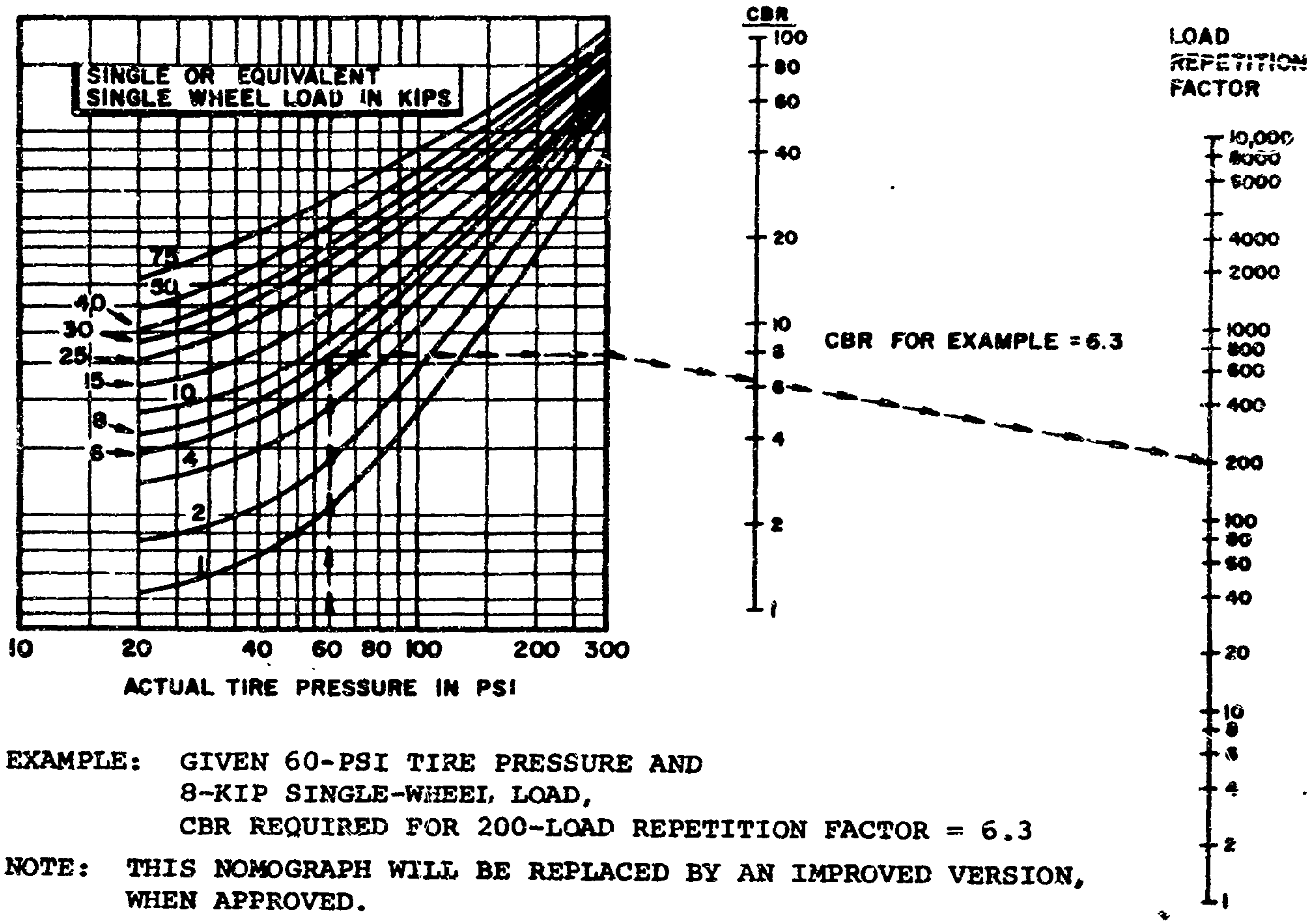
Since the latter part of World War II a number of organizations have conducted systematic studies to correlate the performance of ground vehicles with the properties of the soils over which they travel. In such studies a primary requisite is a means of measuring the pertinent soil properties. Some studies, particularly those of relatively limited scope, employed conventional soil tests and laboratory equipment. However, for studies in which many large-scale tests were to be conducted or where the inherent variability of naturally occurring soils was involved, soil tests were developed that could be made rapidly and at various depths below the surface without extracting samples.

One such test uses the resistance of soil to penetration by a small cone (termed a cone penetrometer) as an index of soil strength. Adapted from the Proctor needle, this cone penetrometer was introduced in trafficability studies at the Waterways Experimental Station in 1946. Since then, the soil penetration resistance value obtained by this means, termed the Cone Index, has been used to correlate the performance of a variety of military vehicles with soil conditions in several thousand field tests. Cone Index is also employed in the laboratory by the WES in more basic research on mobility.

The soil definition for a particular mission may be divided into two classes: mission-constrained minimum soil strength and random soil strength. These two categories are discussed in following paragraphs.

Mission-Constrained Minimum Soil Strength

For many operations, the minimum soil strength at the pickup and delivery point is constrained by the mission. For example, if the mission is to deliver an engineering tractor to a site on which an airfield is being constructed, then it follows that the soil strength at that site must be at least the minimum required to support the tractor. Similarly, if the mission is to transport heavy engineering materials to a location for bridge repair, it follows that the soil is strong enough to enable engineering troops to handle those materials.



EXAMPLE: GIVEN 60-PSI TIRE PRESSURE AND 8-KIP SINGLE-WHEEL LOAD, CBR REQUIRED FOR 200-LOAD REPETITION FACTOR = 6.3

NOTE: THIS NOMOGRAPH WILL BE REPLACED BY AN IMPROVED VERSION, WHEN APPROVED.

FIGURE 3. CALIFORNIA BEARING RATIO REQUIRED FOR OPERATION OF AIRCRAFT ON UNSURFACED SOILS

Definition of the actual soil strength required is made by reference to Technical Bulletin TB-ENG 37 - Soil Trafficability (Reference 13), written by the U. S. Army Corps of Engineers, WES. It is based on measurement of the soil strength by the cone penetrometer and contains data on the minimum soil Cone Index required to support 40 to 50 passes of the same vehicle. The data, which apply to operation in fine-grained soils and those sands which contain enough fine-grained soils to make them behave like fine-grained soils when wet, are based on empirical measurement of vehicle performance. The vehicle performance is summarized into seven categories as follows:

TABLE I. CATEGORIES OF VEHICLE PERFORMANCE

Performance Category	Cone Index Range	Vehicle
1	20-29	The M29 weasel, M76 Otter, and Canadian snowmobile are the only known standard vehicles in this category.
2	30-49	Engineer and high-speed tractors with comparatively wide tracks and low contact pressures.
3	50-59	The tractors with average contact pressures, the tank with comparatively low contact pressures, and some trailed vehicles with very low contact pressures.
4	60-69	Most medium tanks, tractors with high contact pressures, and all-wheel-drive trucks and trailed vehicles with low contact pressures.
5	70-79	Most all-wheel-drive trucks, a great number of trailed vehicles, and heavy tanks.
6	80-99	A great number of all-wheel-drive and rear-wheel-drive trucks, and trailed vehicles intended primarily for highway use.
7	100 or greater	Rear-wheel-drive vehicles and others that generally are not expected to operate off roads, especially in wet soils.

Table II shows the minimum Rating Cone Index necessary for completion of 1 pass and 50 passes (called Vehicle Cone Index) for four military vehicles, a construction tractor, and an agricultural tractor.

TABLE II. VEHICLE PERFORMANCE IN FINE-GRAINED SOILS

Vehicle	Description	Rating Cone Index for 1 Pass	Rating Cone Index for 50 Passes (Vehicle Cone Index)
M29C weasel	5,500-lb, tracked, amphibious cargo carrier	20	25
M48 tank	90,000-lb medium tank	40	50
M37 3/4-ton weapons carrier	7,400-lb (with load of 1,500 lb) 4x4 truck	50	65
M135 2-1/2-ton cargo truck	16,300-lb (with load of 5,000 lb) 6x6 truck	45	60
D7 engineer tractor	35,000-lb crawler-type construction tractor	30	40
Farmall 560 tractor	7,170-lb with tricycle configuration	36	48

Random Soil Strengths

A helicopter may perform some missions in which the soil strength at the landing area is random. These missions include the recovery of damaged aircraft, deployment of foot soldiers, etc. Selection of the limiting soil strengths for such missions must be based on a tradeoff study between mission flexibility and aircraft performance or, more specifically, between flotation and weight, speed, and range. The basis for such a study is a soil strength spectrum for the theater. This soil strength spectrum consists of a plot of soil strength versus percent area. Thus, if a minimum soil strength is selected for a given aircraft, the percentage of total area on which landings may safely be made can be determined. For a

random distribution of missions within a given area, therefore, the percentage of total area is equivalent to the percentage of missions completed in that environment.

The bulk of authoritative soil strength data in the United States is either directly or indirectly attributable to the WES. At one time, some of these data were used to compile soil strength spectra for use in selecting design criteria for military vehicles; however, this facility has recently changed its position on this practice. WES engineers indicate that, as a result of their studies, they have concluded that sufficient field test data are not available to provide more than a gross overall estimate of soil strength that might be available at a given location under existing environmental conditions, even for very small areas.

In military ground vehicle design, this lack of data is not as serious as it would at first seem because, in fact, the off-highway vehicles that are being or have been used are themselves soil measuring devices. The performance of successful vehicles in soft soil under operational conditions is an indication of the performance requirements for the future generation of vehicles. Conversely, deficiencies in unsuccessful vehicles indicate where improvements must be made.

Data of this kind on operation of helicopters are limited; and as operational techniques and sizes of aircraft change, so do the flotation requirements. It is necessary, therefore, to continue efforts to define soil strength data in order to improve the accuracy of flotation requirements predictions for new generations of helicopters.

Soft Soil Flotation Analysis

As previously stated, the requirements for operation in soft soil are that the aircraft may safely lift itself out of the soil or, in some cases, that it be possible to taxi or make running takeoffs. Lift-off capability in soft soils is a very difficult thing to define. In order to understand just what is required, it is necessary to consider the behavior of a helicopter in such a situation. In the first instance, it is important to maintain a substantially level attitude on the ground; the actual tolerance is dependent on helicopter configuration.

Figure 4 illustrates the case of an articulated-rotor helicopter, single or tandem, with one gear submerged in soft terrain,

resulting in a roll angle. In order to take off, the pilot must first put on full lateral stick, resulting in the tip path plane being tilted an amount β towards the horizontal. It is then necessary to pull collective pitch and gradually apply thrust. In the case of the hingeless rotor (Figure 5), when lateral stick is applied the tip path plane tilts a small amount. If the roll angle, ϕ, is large, it is possible for the helicopter to overturn. The criterion for overturning is:

$$\phi \leq B \left(\frac{\ell}{h} + 1\right) + \frac{M}{T.h} \qquad (2)$$

For a teetering rotor, the hub moment, M, is zero; therefore, typically, the overturning angle is 2M, or twice the maximum lateral tip path tilt. Articulated-rotor helicopters with a flap hinge offset exhibit a hub moment which is approximately proportional to the hinge offset. The hub moment for articulated-rotor helicopters is typically equal to that due to tip path tilt. Hingeless-rotor helicopters are limited in the amount of tip path tilt, but make up for this with increased hub moment. Practical hingeless-rotor helicopters exhibit a lateral control power only slightly in excess of articulated-rotor helicopters. Figure 5 shows a plot of lateral righting moment as a function of hinge offset. Note that a condition for overturning is that a wheel must be prevented from moving laterally; it is not necessary for it to be stuck.

The lift-off capability of a helicopter is intimately allied to the sinkage of the landing gear; thus, in order to assess this capability, it is necessary to predict that sinkage. Prediction of gear sinkage of military ground vehicles in soft soil is a subject which has received much attention since World War II. The two major agencies working in this area are:

1. Army Tank Automotive Center (ATAC), Land Locomotion Laboratory

2. U. S. Army Corps of Engineers, Waterways Experimental Station (WES)

The different approaches used by these agencies in analyzing vehicle sinkage are discussed in the following paragraphs:

ATAC Land Locomotion Method

The approach to the analysis of vehicle locomotion at the Land Locomotion Laboratory of the Army Tank Automotive

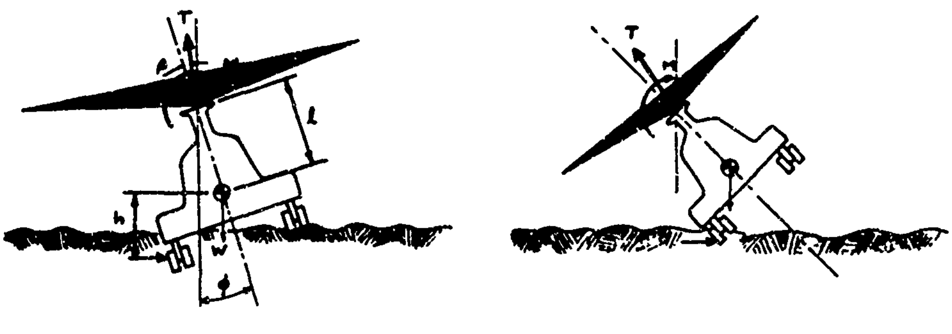


FIGURE 4. TAKEOFF OF A HELICOPTER WITH ONE LANDING GEAR IMMERSED IN SOFT SOIL

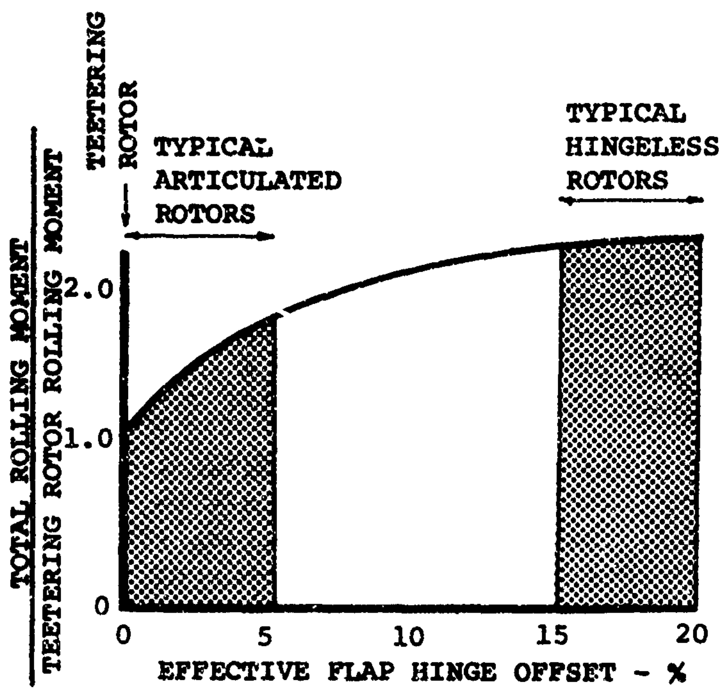


FIGURE 5. COMPARISON OF APPROXIMATE LATERAL CONTROL POWER FOR VARIOUS TYPICAL HELICOPTER CONFIGURATIONS

Center was developed by M. G. Bekker (References 1, 2 and 3). The basis of Bekker's method is the adequate description of the parameters involved in soil mechanics. Bekker took a foundation sinkage formula proposed by Russian investigators in which ground pressure (p) is given by

$$p = k \cdot z^n . \tag{3}$$

Bekker postulated that, while the soil exponent, n, was independent of loading area, the same could not be said of the soil modulus, k. Bekker proposed an increase in degrees of freedom for this parameter. This new formula for the soil modulus is

$$k = \frac{k_c}{b} + k_\phi . \tag{4}$$

Symbol b = width of footing in inches and the parameters k_c and k_ϕ are empirically derived from fitting pressure sinkage curves to data measured with a device known as a Bevameter. The Bevameter is an instrument which hydraulically loads a bearing plate and measures its load and sinkage relations. Tests performed with plates of various sizes provide the data required to predict k_c and k_ϕ.

Equation (4) shows that k is dependent upon the size of the loading area; for a given loading area, the sinkage will be a minimum when the aspect ratio is a maximum. The application of this basic theorem to helicopter landing gear indicates that, from a sinkage standpoint, a skid is more efficient than a pad.

The basic sinkage equation was used to develop sinkage equations for ski, track, pneumatic-tire, and rigid-wheel landing gear. Ski and track equations simply describe the ground pressure, p, in terms of their load and geometry.

The pneumatic tire is treated in two ways. First, when the soil considered is sufficiently strong to allow the tire to form a footpoint, the ground pressure is assumed to equal the tire inflation pressure plus an increment of pressure due to the carcass stiffness.

Second, in very weak soils where the soil is not sufficiently strong to support the load through a footprint,

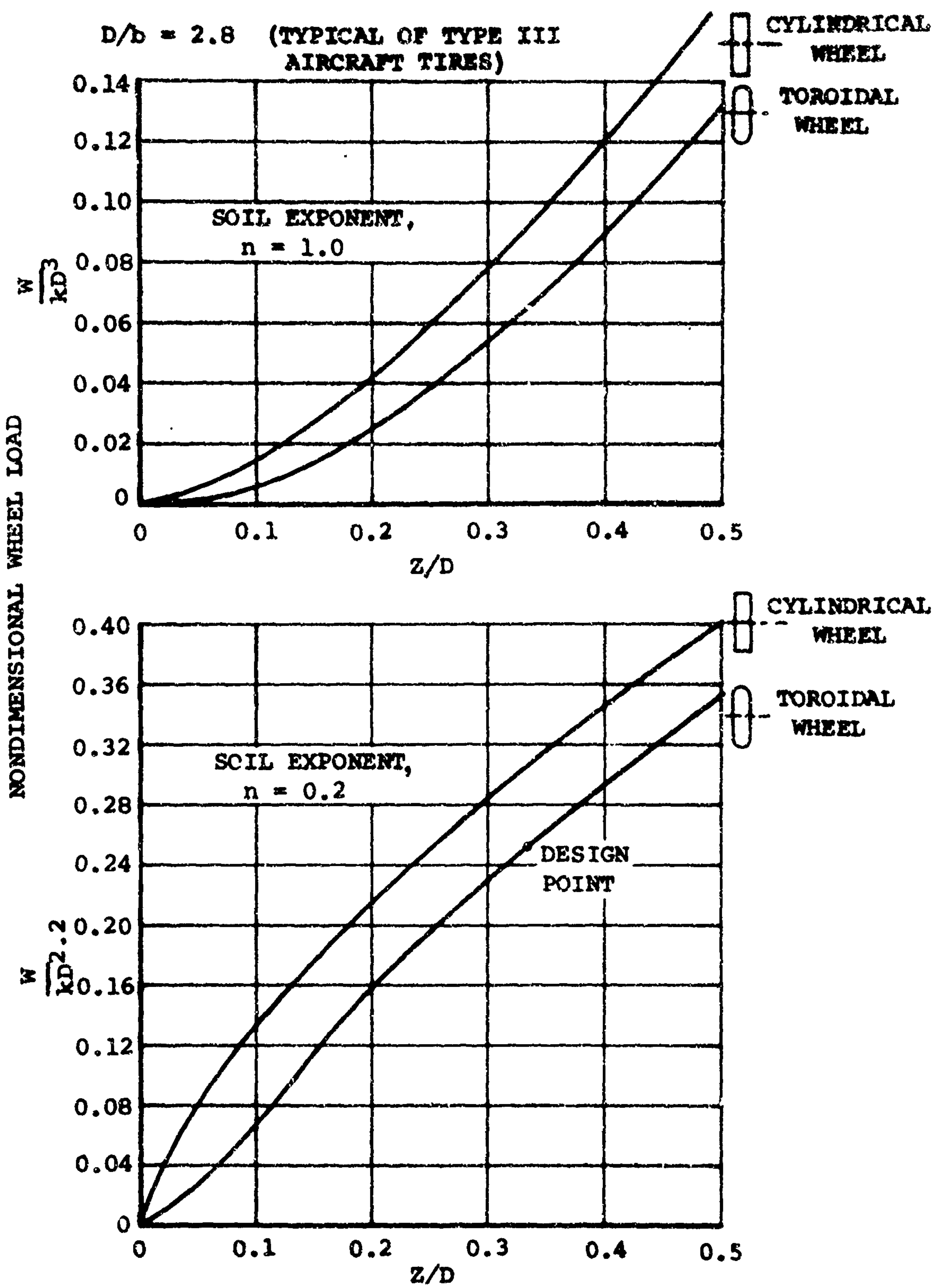


FIGURE 6. LOAD-BEARING CAPACITY OF RIGID WHEELS IN SOFT SOILS

the tire is considered to behave like a rigid wheel of equivalent geometry. The sinkage of rigid wheels is predicted by integrating the sinkage equation over the immersed volume of the wheel and equaling this to the load. Bekker's analysis considered only wheels with cylindrical shapes; it was, therefore, necessary to compute new sinkage relations for toroidal-shaped aircraft wheels. The results of this analysis are shown in Figure 6.

In 1959 an ad hoc Committee on Off-Road Ground Mobility Research was appointed by the Chief of Research and Development, Department of the Army, to review the military ground mobility research activities in the United States. This committee pointed out the desirability of translating measurements of soil properties from one system to another. To date, two reports (References 11 and 12) have been published on comparison of soil measurements, one in dry and the other in wet fine-grained soils (clay).

From the aircraft flotation standpoint, fine-grained soils would appear to present the greatest problem. Correlation of Cone Index and Soil Modulus in fine-grained soils from Reference 14 indicates

$$k_c = 0.19 \text{ CI}$$

$$k_\phi = 0.48 \text{ CI}$$

$$\text{and } n = 0.2 \,.$$

So for the soil strength range CI greater than 10 and for wheel (footprint) widths greater than 10 inches, the influence of k_c is negligible, and it can be assumed equal to 0.5 CI. This value will be used in comparison of sinkages.

Definition of sinkages conducive to uniform, safe lift-off has not been attempted analytically; however, guidelines may be established by consideration of the physical problem.

In the case of ski or pad gear, experience with snow skis used in soft soil has indicated that the cohesion between ski and soil is not sufficient to impair lift-off

capability. Lift-off could be prevented, however, if the ski were to sink deep enough to allow the soil to flow over the top and so bury the ski. A design maximum sinkage of about 4 to 5 inches appears to be a reasonable goal.

The criterion for wheel-type gear is similar to that for ski-type; that is, it is undesirable to allow the wheel to sink so that soil may close back over the wheel. This problem is accentuated in wheel-type gear since, if the sinkage is more than D/2, the wheel acts like a piston during removal and substantial hydraulic resistance may ensue. A reasonable design maximum sinkage appears to be about D/3; at this level, movement of the wheel ventilates the rut so that the possibility of hydraulic resistance is minimized. The D/3 sinkage criteria were used in the analysis contained in this report.

It should be noted that tests performed by WES with the CH-47A helicopter operating from soft Mississippi clay showed that the aircraft was capable of landing and lifting off in soils down to CI-4. At CI-25 the wheels were completely immersed, and in softer soils the aircraft rested on its belly. It may be that design criteria for transport helicopters could be developed to include the flotation of the aircraft belly. Such a technique is not possible with crane-type helicopters, however.

The limitations of this method are that the sinkages of surface and deeply buried footings are not defined; also the sinkage of different-sized tires of the same pressure is not accounted for. It does, however, serve as a useful check on other methods, and agreement with measured sinkages of the CH-47A was quite acceptable.

It must be emphasized that none of these methods and criteria for predicting aircraft landing gear flotation in soft soil are officially approved, but no other methods exist at this time. Since the concept of airmobile forces which place emphasis upon rapid mobility seems to be increasing in importance, it is recommended that a comprehensive test program be established to define such methods and criteria.

Waterways Experimental Station Methods

While ATAC is primarily concerned with vehicle mobility, WES interest lies in the trafficability of soils. Soil strength in WES work is expressed as a Cone Index. This is measured by the cone penetrometer and is expressed as the force required to push a rod of half-square-inch cross-section area with a 30-degree conical point into the soil. The Cone Index is a measure of the shear strength of the soil. The ability of the soil to sustain repeated passes is indicated by measuring the strength of a remolded soil sample. Remolding Index is the ratio of the remolded strength to the original strength. Rating Cone Index (RCI) is the measured Cone Index multiplied by the Remolding Index and is an indication of the trafficability of the soil under repeated passes.

WES engineers have determined, by test, the Vehicle Cone Index (VCI) for all Army ground vehicles operating in soft soil. The VCI indicates the maximum soil strength in terms of RCI required for 40 to 50 passes. The cone penetrometer is the standard soil-strength measuring device issued to the U. S. Army as part of the Test Set-Soils Trafficability. The use of the cone penetrometer as well as the VCI of Army vehicles is described in Reference 13.

Recently, the Mobility Research Branch of WES under Dr. D. Freitag has developed analytical techniques to predict vehicle ground mobility based on empirical data and Cone Index description of soil strength. These methods (described in Reference 5) treat cohesive frictionless soils (clay) and noncohesive frictional soils (sand) separately. It is argued that the mobility of any particular vehicle configuration is critical either in sand or in clay and not usually in a composite soil; therefore, the definition of mobility in sand and clay describes the lower boundary of the problem.

The data for using this method are currently limited to sinkages of D/10 and, therefore, do not cover the range necessary for this study.

In their tests on the CH-47A in cohesive soils, WES engineers compared the sinkage with the theoretical value for a footing in cohesive soil (Reference 7). These data

were applied to the general problem of aircraft tire sinkage, and the results are presented in Figure 7.

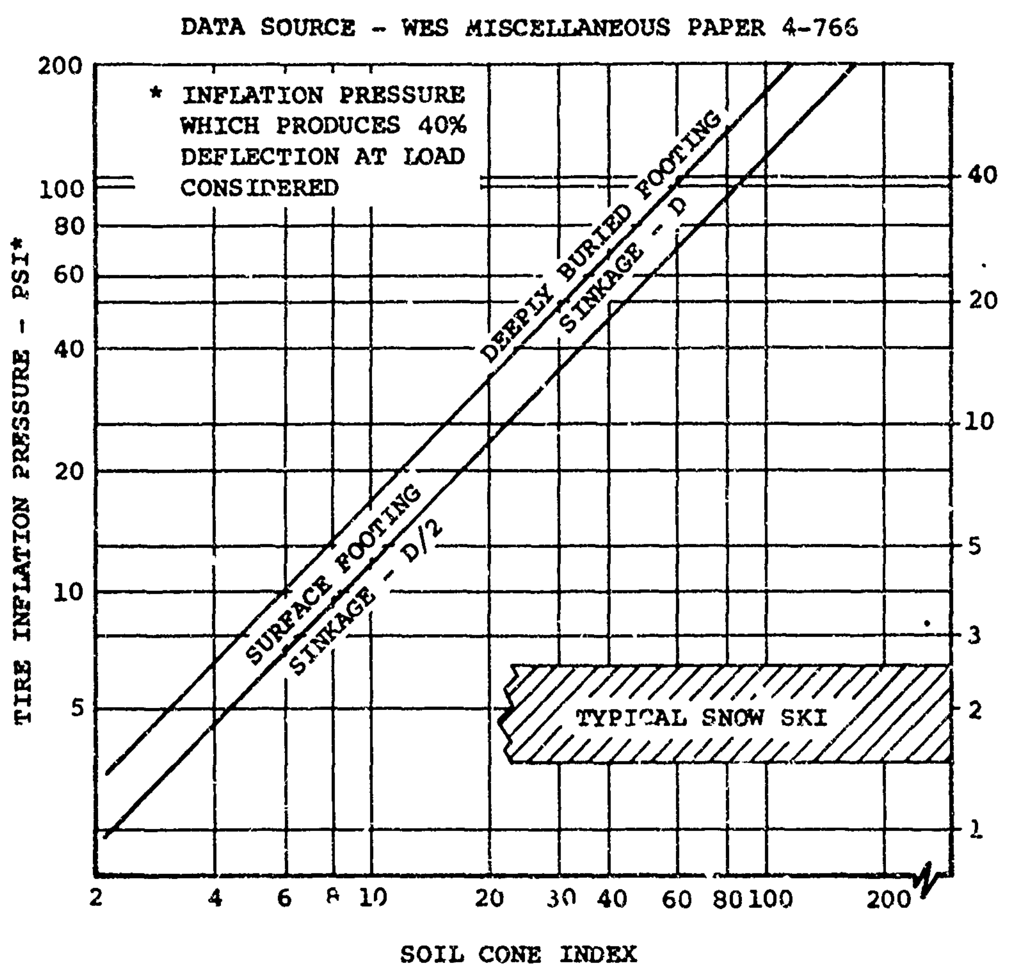


FIGURE 7. THEORETICAL DEEP SINKAGE OF TYPE III AIRCRAFT TIRES IN COHESIVE SOIL

(C) MISSION ANALYSIS (U)

(U) This portion of the study analyzes the missions projected for the Heavy Lift Helicopter (HLH). It is based on certain general assumptions and conducted within stipulated constraints drawn largely from the draft Qualitative Materiel Requirement (QMR) for the Army Heavy Lift Helicopter. These assumptions and constraints are listed later in this section. The analysis is directed to the examination of tactical environment in Southeast Asia, Western Europe, and the Continental United States. These areas were selected as representative of conditions which would govern future military operations. The basic loads and missions analysis from which the following data were derived was performed by Vertol Division of Boeing and is described in Reference 9.

(U) The objectives of the analysis are to provide a credible military operations data base for analyses of design considerations for this aircraft by examining the following characteristics of military operations:

1. Probable geographical areas in which the HLH may be expected to be used in the performance of military tasks.

2. The tasks or missions which would be assigned to either a crane or transport version of the HLH.

3. The operational and environmental constraints affecting HLH mission capabilities.

4. The characteristics of the cargo to be transported by the HLH.

5. The required mission distances and frequencies necessary to perform the assigned tasks.

6. The manner of loading and unloading (i.e., internal or external), ground handling requirements, etc.

7. Takeoff, landing, and ground maneuvering requirements.

8. Daily frequency of sorties (as a function of loads required).

9. Cyclic rates at the points of departure and delivery.

(U) GENERAL ASSUMPTIONS

This analysis makes the following basic assumptions:

1. The HLH will be employed primarily in providing logistical mobility to the Field Army Support Command (FASCOM).

2. The materials handling equipment and personnel will be available to load/unload the HLH in any of the load acquisition options specified in the QMR.

3. Selection of either the transport or the crane configuration for individual mission application will be a function of:

   a. The physical nature of the load to be transported.*

   b. The nature of the mission (radii, speed, altitude, loading and unloading techniques, etc.).

4. The makeup of the various forces selected for employment within the theaters of operation implies that organic air transport is available to accomplish the more normal missions of personnel deployment and resupply to combatant elements.

5. Because of its size (presenting a large and attractive target) and its expense, the HLH will not ordinarily be committed to situations in which there is a high probability of exposure to enemy fire.

(C) DRAFT QMR CONSTRAINTS (U)

The analysis is conducted within the framework of the following constraints:

*Since universal containerization is not in operational use today, loads are considered as they are presently packaged. If containerization is subsequently considered, the results of this analysis could change appreciably.

1. The HLH will be used for aerial transport of heavy loads which cannot be lifted by other organic Army helicopters.

2. In primary mission configuration, the HLH shall be capable of hover out of ground effect (OGE) with a 13-ton payload under 4000-foot/95°F ambient conditions and shall be capable of hover in ground effect (IGE) with a 17-ton payload under the same ambient conditions.

3. The HLH shall be capable of hovering with payload for 10 minutes and without payload for 20 minutes.

4. The HLH shall be capable of making four 25-nautical-mile-radius trips with payload outbound and without payload inbound, while retaining a fuel reserve equal to 10 percent of initial fuel.

5. The HLH shall be configured to allow sling loads, special-purpose rigid containers, positive-attachment/rapid-disconnect general-purpose pods or cargo platforms; or a large-cross-section cargo compartment shall be provided, with the primary means of payload transport still being through external carriage of loads.

6. The HLH shall be capable of delivering cargo by landing or by winching down from a hover.

7. The establishment of local air superiority shall be a requirement for operation of the HLH.

8. The HLH shall be capable of operating with 200-foot ceiling and 1/2-mile visibility in daylight or darkness.

9. The HLH shall be capable of operation in all areas of the world where United States forces may be deployed.

(C) <u>DRAFT QMR OPERATIONAL TASKS</u> (U)

As specified in the draft QMR, the HLH will perform assorted tasks using either external or internal means of carrying the loads. It will be employed singly or by sections, platoons, and companies in the Division, Corps, Field Army, Support

Command, and Theater logistical units for combat support and command service support tasks. It will be used in airmobile operations. Tasks will include the following:

1. Support of obstacle-crossing operations including the lifting of special equipment and outsized items across obstacles.

2. Aerial movement of selected Corps of Engineers equipment including the Universal Engineer Tractor, scoop loaders, and construction and barrier equipment.

3. Recovery and extraction of ground and air vehicles including heavy vehicles; e.g., the Armored Reconnaissance Airborne Assault Vehicle (AR/AAV) weighing 16.5 tons, the MIVC-70 weighing 15 tons, downed Army aircraft, and aircraft of other services. It will also include replacement and efficient evacuation of airmobile and armored units.

4. Movement of special unit modules including command posts, signal centers and automatic data processing units, mobile medical units, air traffic regulation and control units, and aerial processing and interpretation units.

5. Aerial transport of bulk critical items including Class III (vehicle fuel), Class IIIA (aviation fuel), Class IV (miscellaneous engineering equipment, etc.), and Class V (ammunition) materials. Flexible fuel cells of 2,500 and 5,000 gallons will be transported in support of airmobile operations.

6. Performance of Class II and Class IV requirements to displace a Field or General Army depot.

7. Participation in logistics over the shore (LOTS) operations.

8. The displacement of heavy-equipment combat units including Air Defense artillery, Field Army armored personnel carriers, etc.

9. Ship-to-shore cargo offloading at terminal ports including direct supply to railheads, and supply points, if necessary, to relieve congestion at ports.

10. The support of pipeline and rail-laying operations.

(U) DEVELOPMENT OF THE MISSIONS

The specific HLH missions discussed in this section were developed in answer to the unique requirements of the tactical situations under consideration. Each mission description includes a definitive identification of the point of departure and destination. The frequencies of the several missions to these geographical points are developed to yield usage rates which, when combined with the surface capacity and the aircraft gross weight, will form the basic guidelines for landing gear design considerations. Deviation from these established points of departure and arrival into completely unprepared areas will not normally occur. The obvious exception is in the event of an emergency. In this case, a landing will be effected in the manner and where the nature of the emergency dictates. Personnel safety will be the paramount concern and aircraft recovery a secondary consideration.

(U) MISSION ANALYSIS - BANGKOK AREA

In answer to a threat from the north aimed down the Chao Phraya Delta, tactical forces have been introduced into Thailand through the Bangkok port complex and by strategic sealift and airlift. Prepositioned stockpiles of supplies are assumed adequate to support two Thai Divisions and one U.S. Infantry Division engaged in delaying operations in Northern Thailand during the first 15 days of combat.

In support of the overall time-phased buildup of combat forces in Thailand, two major tasks must be accomplished:

1. Clearance and clean-up of the port proper, which will of necessity require the establishment of a dispersal complex to permit transfer of bulk tonnage from the port area to accessible distribution points.

2. Establishment and/or maintenance of ground transport routes and air facilities to ensure adequate and uninterrupted lines of communication in support of operations in the combat zone.

Table III is a log of the missions performed in the Bangkok area.

(U) MISSION ANALYSIS - CAM RAHN BAY AREA

The enemy has successfully established an infiltration route from the northwest, from which significant numbers of troops are building up in the area to the west of Cam Rahn Bay.

In answer to this threat, tactical elements are rapidly moving into the port complex of Cam Rahn Bay by sea and airlift, for further deployment inland (to the west) to defensive positions in close proximity to the enemy. Additional tactical units will reinforce these initial positions and conduct "search and destroy" operations forward of the defensive positions. Deployment to the forward areas and support of these elements will be essentially by organic air transport.

The primary mission of the HLH in this situation is logistical, with emphasis on the establishment and supply of forward (inland) support bases. The limitations of inland ground routes (non-availability and vulnerability) will place heavy reliance on air transportation for the resupply mission in the early phases of the operation. Table IV is a log of the missions performed in this area.

(U) MISSION ANALYSIS - BREMERHAVEN AREA

An enemy force of substantial strength has massed to the east and is crossing the North German plain. The heart of the approaching force is reported to be heavy armor.

A defensive perimeter must be established immediately, to secure the port complex of Bremerhaven. In addition, the port complex is assumed to have suffered considerable damage from enemy air attack. Road and rail networks and harbor facilities at Bremerhaven, Hamburg, and Wilhelmshaven have suffered some degree of damage which has reduced their throughput capacities.

Eight air facilities exist within a 50-nautical-mile radius of Bremerhaven (the HLH operating sphere). Even though damaged, these facilities would provide adequate landing points for the HLH under almost any condition of weather. In addition, the area is generally well drained, comparatively open, and would require a minimum of effort by Corps of Engineers units to provide serviceable pioneer landing sites.

The mission of the HLH in this situation is, therefore, to provide general logistical mobility for the Service Support

Forces of Theater and special tactical mobility for the Field Army. Table V is a log of the missions performed in the Bremerhaven area.

(U) MISSION ANALYSIS - OAKLAND AREA

Any requirement for a buildup of U.S. Forces in the western Pacific area would generate a substantial increase in military traffic in the Oakland area. It is assumed that a part of this traffic is the high-priority movement of an Army ROAD Division from Continental United States, through the Oakland Military Overseas Terminal. Movement to the port of embarkation has commenced, using rail, commercial truck, and limited Government-owned or contracted air carriers. The dock, rail, roadway, and storage facilities of San Francisco Bay area are operating at near capacity, and this priority movement will impose a burden that will severely tax all capabilities.

The primary mission of the HLH in the situation just described is to provide logistical mobility which will permit the scheduled delivery of various items of heavy equipment and hazardous materiel to dockside, avoiding congested metropolitan areas. Task missions consist of delivery missions from staging areas to loading points. Mission radii range from 8 to 54 nautical miles. Pickup and delivery points are surfaced with blacktop or concrete. Table VI is a log of the missions performed in the Oakland area.

(U) CARGO HANDLING

The HLH will be equipped with single-point and multi-point hoist systems. Choice of hoist system for each mission depends upon the load, mission distance, ground facilities, and landing surfaces at source and destination points. As discussed in Reference 8, cargo handling systems influence landing gear design by contributing to the definition of operating mode and aircraft weight condition for each type of load acquisition.

In general, a single-point-suspended load will be acquired from a hover or by landing alongside; the weight of the load will not usually be felt by the landing gear. Multi-point suspension of large vehicles, missiles, bridge sections, etc., also requires a hover pickup since, unless rigidly restrained, large loads will not be carried close to the fuselage. This is because the clearance between the long landing gear and the

load would not be large enough to preclude damage by inflight contact.

The only forms of load which will be straddle-loaded (thus imposing a maximum gross weight condition on the landing gear) will be pods and containers rigidly attached to the aircraft and those loads which when hoisted close to the fuselage have sufficient clearance to ensure that damage to the aircraft will not occur. Compact high-density loads fall into this category; these include ammunition and POL containers. However, these loads usually fly very well on single-point suspension, so that there would be no advantage in using multi-point. Some classes of ground vehicles also fall into this category but, once again, in many instances these loads fly quite well on single-point. Recent tests conducted with the CH-47 transporting a 3/4-ton truck by single-point suspension have shown that when properly rigged this load may be flown at speeds up to 125 knots.

The requirement to couple the load closely in order to make straddle acquisition normally precludes the use of a sling, so that it is necessary for the load to be equipped with lifting attachments compatible with the aircraft hoisting system.

For these reasons, ground mobility will not be required in unprepared terrain and only limited ground mobility may be required on prepared surfaces, for the acquisition of pods.

(U) SUMMARY OF LANDING AREAS

The most significant feature of the missions defined by the foregoing analysis is the absence of a highly repetitive mission such as would be the case if the HLH were to be a link in an air line of communication. The QMR constrains the HLH utilization to a series of specialized tasks associated with the transportation of outsized loads; normal resupply-type loads will be carried only when they take precedence. In this role the HLH will not normally subject any one landing area to high coverage rates.

A summary of landing areas derived from the above detail mission analysis is presented in Table VII. In fact, these are pickup and drop locations for those missions; in most cases the aircraft would not be required to land. The maximum usage rate on any one mat-surfaced airfield (TO support-area airfield) is 97 passes per week, for the Cam Rahn Bay area.

Operations to and from unsurfaced soil were presented only in the Bangkok and Cam Rahn Bay areas. All operations from unsurfaced soil in the Bangkok area fall into the category of mission-defined minimum soil strength as defined in the Landing Gear Flotation section. Of the 26 unsurfaced soil missions, 23 were in support of engineer operations and involved delivery of either vehicles or materials. The three remaining missions consisted of the delivery of medical supplies, a 1/4-ton truck, and personnel in order to control a cholera outbreak.

Breakdown of unsurfaced soil missions in the Cam Rahn Bay area shows 146 operations from TO forward-area airfields; the maximum number of weekly operations from any one field is 78. One operation falls into the category of mission-constrained minimum soil strength; this involves the delivery of an engineering bulldozer. One mission called for towing of a grounded landing craft, with no landing required. Three missions are involved with placement of radar and communications modules. These could possibly be placed on soft soil, but it is most unlikely that they would be sited on very soft or swampy ground. The one remaining mission, the recovery of a downed aircraft, may require landing in soil of almost any strength.

TABLE III. (U) HLH MISSION LOG - BANGKOK, THAILAND AREA

Mission No.	No. of Sorties	P/U Point	Drop Zone	Type Surface	Dist (NM)	Sling or Internal	Flight Alt (Ft)	Flight Time (Min)	Total Weight (Lb)	Supply Class
1	4	FDL QQ 0263	QQ 0770	Dirt	5	Sling	500	5	65,200	II &
	16	"	"	"	"	"	"	"	90,582	IV
	30	"	"	"	"	"	"	"	679,920	
	2	"	"	"	"	"	"	"	54,300	
	20	"	"	"	"	"	"	"	118,340	
	72								1,008,342	
2	2	PR 7205	PR 7016	Crushed Stone	7	"	500	7	56,800	
	2				"	"	"	"	54,300	II &
	2	"	"	"	"	"	"	"	40,000	
	10	"	"	"	"	"	"	"	226,640	IV
	1	"	"	"	"	"	"	"	18,400	
	17								396,140	
3	2	PR 7205	QQ 1685	Laterite	25	"	500	15	56,000	IV
4	3	PR 7016	PR 7539	Concrete	13	"	500	8	29,115	II &
	1			"	"	"	"	"	20,300	IV
	4								49,415	

TABLE III. (U) HLH MISSION LOG - BANGKOK, THAILAND AREA (CONT)

Mission No	No. of Sorties	P/U Point	Drop Zone	Type Surface	Dist (NM)	Sling or Internal	Flight Alt (Ft)	Flight Time (Min)	Total Weight (Lb)	Supply Class
5	1	QQ 0769	PR 7348	Crushed Stone	45	Sling & Internal	1,000	25	18,400	I, II & IV
6	1	PR 7205	PR 7348	Laterite	17	Sling	500	10	31,360	IV
7	1	PR 7539	QR 5858	Sod	46	Sling & Internal	1,000	25	18,560	I, II & IV
8	1	PR 7016	PR 7539	Concrete	13	Sling	500	8	36,000	II & IV
9	2	PR 7016	PR 7539	Concrete	13	"	"	"	24,000	II & IV
10	2	PR 7205	PR 7539	Hard Stand	10	"	"	6	52,800	II & IV
11	10	PR 7201	PR 7303	"	1	"	"	3	130,000	II & IV
12	10	PR 7016	PR 7246	PSP	16	"	"	10	348,480	V

TABLE III. (U) HLH MISSION LOG - BANGKOK, THAILAND AREA (CONT)

Mission No.	No. of Sorties	P/U Point	Drop Zone	Type Surface	Dist (NM)	Sling or Internal	Flight Alt (Ft)	Flight Time (Min)	Total Weight (Lb)	Supply Class
13	4	PR 7016	PR 7235	PSP	11	Sling	500	7	70,000	II & IV
14	2	PR 7539	QR 5858	Sod	46	Sling & Internal	1,000	25	26,000	I, II, & IV
15	3	PR 7016	PR 7235	PSP	11	Sling	500	9	108,000	II & IV
16	2	PR 7016	PR 7539	Concrete	13	"	"	10	72,000	II & IV
17	35	PR 7016	PR 7348	"	17	"	"	12	1,260,000	V

Total = 249 Sorties at 13.2 Short Tons/Sortie

Total = 3,016 NM at 12 NM/Sortie

Total = 6,585,497 lb at 3,298 Short Tons

(Missions 1 through 14 are one-time requirements to develop the supply complex.)
(Missions 15, 16, & 17 are representative of bulk tonnage dispersal to the supply complex above.)
(Missions 15, 16, & 17 are daily requirements, and are repeated for 17 July & 18 July.)

TABLE IV. (U) HLH MISSIONS LOG - CAM RAHN BAY, SOUTH VIETNAM AREA

Mission No.	No. of Sorties	P/U Point	Drop Zone	Type Surface	Dist (NM)	Sling or Internal	Flight Alt (Ft)	Flight Time (Min)	Total Weight (Lb)	Supply Class
1	2	BP 9514	BP 5008	Dirt	24	Sling	1,000	15	40,000	IV
2	2	BP 4710	BP 5008	"	2	"	500	5	25,400	IV
3	1	CP 0452	BP 8885	"	22	"	1,500	15	31,900	IV
4	1	BP 7814	CP 0516	Hard	16	"	1,500	12	25,000	II
5	1	BP 9509	BP 9509	Mud	0	"	50	Un-known	Max Try (Tow)	Tow
6	1	CP 0516	CP 0452	PAP	20	"	1,500	15	24,000	IV
7	1	CP 0516	CP 0452	Plank & Sod	20	"	1,500	15	37,600	IV
8	2	BP 9514	BN 7980	Plank	20	"	1,500	12	28,290	IV

TABLE IV. (U) HLH MISSIONS LOG - CAM RAHN BAY, SOUTH VIETNAM AREA (CONT)

Mission No.	No. of Sorties	P/U Point	Drop Zone	Type Surface	Dist (NM)	Sling or Internal	Flight Alt (Ft)	Flight Time (Min)	Total Weight (Lb)	Supply Class
9	3	CP 0452	BP 5579	Plank & Sod	22	Sling	1,500/ 6,000	15	65,845	IV
1A	1	CP 0516	BP 7090	Dirt	48	"	2,500	32	31,360	IV
2A	3	CP 0516	BP 1922	Sod & Laterite	49	"	1,500	28	50,400	IV
3A	1	CP 0452	BP 5965	Sod	27	"	1,500	16	27,840	IV
5A	1	CP 0516	BP 5965	PSP	40	"	1,500	22	27,950	II, III, & IV
7A	1	CP 0452	BP 7090	PSP	32	"	1,500	18	21,600	IV
8A	1	CP 0516	BP 5965	PSP	40	"	1,500	22	30,800	V
9A	3	CP 0516	BP 1922	Sod & Laterite	49	"	1,500	28	92,928	V
9B	1	CP 0452	BP 7090	PSP	32	"	1,500	18	27,000	III

TABLE IV. (U) HLH MISSIONS LOG - CAM RAHN LAY, SOUTH VIETNAM AREA (CONT)

Mission No.	No. of Sorties	P/U Point	Drop Zone	Type Surface	Dist (NM)	Sling or Internal	Flight Alt (Ft)	Flight Time (Min)	Total Weight (Lb)	Supply Class
9C	1	CP 0516	BP 5965	PSP	40	Sling	1,500	22	27,000	III
10	3	CP 0452	BP 5965	Sod	27	"	1,500	18	108,000	II & IV
11	3	CP 0516	BP 1922	Sod & Laterite	49	"	1,500	32	108,000	II & IV
12	5	CP 0516	BP 5965	PSP	40	"	1,500	26	200,000	III
13	20	CP 0452	BP 7090	PSP	32	"	1,500	21	800,000	V
14	20	CP 0516	BP 1922	Sod & Laterite	49	"	1,500	33	800,000	V

Total = 170 Sorties at 19.6 Short Tons/Sortie

Total = 6,836 NM at 40.2 NM/Sortie

Total = 6,662,913 lb at 3,331 Short Tons

(Missions 1 through 9 and 1A through 9C are one-time requirements to develop the supply complex.)
(Missions 10 through 14 are representative of bulk tonnage dispersal to the supply complex above.)
(Missions 10 through 14 are daily requirements, and are repeated for 7 August and 8 August.)

TABLE V. (U) HLH MISSION LOG - BREMERHAVEN, GERMANY AREA

Mission No.	No. of Sorties	P/U Point	Drop Zone	Type Surface	Dist (NM)	Sling or Internal	Flight Alt (Ft)	Flight Time (Min)	Total Weight (Lb)	Supply Class
1	17	ME 7138	MD 4960	Concrete	41	Sling	1,500	28	544,000	II
2	17	ME 8068	ND 1865	"	55	"	1,500	35	544,000	II
3	8	ME 4535	MD 8578	"	35	"	1,500	24	288,000	IV
4	10	ME 7138	ND 2884	"	39	"	1,500	25	293,000	IV
5	12	ME 7138	NE 3338	"	31	"	1,500	18	264,000	II

Total = 64 Sorties
at 14.6 Short Tons/Sortie

Total = 201 NM
at 40 NM/Sortie

Total = 1,873,000 lb
at 937 Short Tons

(First 3 days of operation)

TABLE VI. (U) HLH MISSION LOG -- OAKLAND, CALIFORNIA AREA

Mission No.	No. of Sorties	P/U Point	Drop Zone	Type Surface	Dist (NM)	Sling or Internal	Flight Alt (Ft)	Flight Time (Min)	Total Weight (Lb)	Supply Class
1	1	Ham-ilton AFB	Port Chi-cago	Concrete	22	Sling	1,500		37,960	V
2	12	Sto-ckton	Ft Mason	"	54	"	"		374,400	II
3	3	"	MOT Oak.	"	48	"	"		110,400	II
4	3	NAS Moff-ett	Port Chic-cago	"	52	"	"		108,416	V
5	4	MOT Oak.	Ft Mason	"	8	"	"		122,000	IV
6	13	Tra-vis AFB	MOT Oak.	"	32	"	"		374,400	II
7	6	NAS Moff-ett	"	"	26	"	"		171,600	II

TABLE VI. (U) HLH MISSION LOG - OAKLAND, CALIFORNIA AREA (CONT)

Mission No.	No. of Sorties	P/U Point	Drop Zone	Type Surface	Dist (NM)	Sling or Internal	Flight Alt (Ft)	Flight Time (Min)	Total Weight (Lb)	Supply Class
8	2	NAS Ala-meda	Port Chi-cago	Concrete	27	Sling	1,500		73,600	V
9	12	"	Ft Mason	"	10	"	"		98,400	II
10	6	Sto-ckton	Port Chi-cago	"	32	"	"		206,000	V
11	10	Hay-ward	Ft Mason	"	19	"	"		280,000	II
12	22	Tra-vis AFB	Port Chi-cago	"	13	"	"		792,000	III

Total = 94 Sorties at 14.7 Short Tons/Sortie   Total = 2,416 NM at 25.7 NM/Sortie   Total = 2,749,000 lb at 1386.0 Short Tons

TABLE VII. (U) SUMMARY OF LANDING AREAS BY SURFACE TYPE

Type of Surface	No. of Sorties Per Week			
	Bangkok	Cam Rahn	Bremerhaven	Oakland
Concrete	134	0	150	94
Shipboard	82	0		
Secondary Road (Stone, Laterite, Dirt)	227	8		
PSP	29	199		
Bare Soil	26	152		

(U) LANDING GEAR CONFIGURATIONS

Selection of landing gear flotation criteria for an aircraft is made by performing a tradeoff between the amount of flotation to be provided and vehicle performance. Therefore, in order to quantify the data involved in this tradeoff, a study was made to determine the weight and effect on maximum speed and range of various landing gear configurations applied to two basic heavy lift helicopter configurations shown in Figures 8 and 9. The performance of these helicopters was analyzed in detail in a recent rotor configuration study (Reference 15) performed for USAAVLABS. The basic configurations are:

1. Model 237 Crane-Personnel Carrier - Gross Weight 84,669 pounds, Tricycle Landing Gear Arrangement.

2. Model 227 Transport - Gross Weight 87,000 pounds. For the purpose of this study the transport configuration was assumed to have a quadricycle landing gear arrangement.

The landing gear longitudinal location was selected so that, for extreme CG travel, the maximum load on each strut would be equal. This produces a well-balanced design but may not be the best location for all aircraft configurations. However, it was felt that the best accuracy would be achieved this way, since it was then possible to analyze for more design cases.

Detail design data were obtained by making layout sketches of shock struts and wheel assemblies. These drawings were made with a range of tire sizes for single, twin and twin-tandem wheel arrangements for both crane and transport configurations. Two wheel sizes for each wheel arrangement were then selected and subjected to a loads, component-sizing, and detail weights analysis. Load factors, materials, and design practices were compatible with current state of the art.

Although, for the purpose of simplifying the analysis, a twin-tandem wheel arrangement was considered fitted to the nose or steered gear, it would be bad design practice actually to build such an arrangement. This is because of the extreme difficulty that would be involved in turning. In a landing gear analysis intended for an actual helicopter, flotation criteria necessitating a large number of wheels would be handled by moving the CG towards the main gear and using twin nose gear

tires or twin duals (four wheels in line).

Initial studies indicated that for multiwheel gear arrangements the optimum lateral tire center-to-center spacing was equal to four contact patch (footprint) radii. This is due to the factors affecting the equivalent single wheel load (ESWL) in the flotation analysis. At and above this spacing the ESWL is equal to the single wheel load, but below this value there is a sharp increase in ESWL. The weight and drag increases associated with increased spacing are small compared with the weight increase resulting from larger tires and lower pressures necessary when mounting the wheels closely. This conclusion may not be valid for retractable landing gear where stowage volume is of paramount importance.

DISCUSSION OF LANDING GEAR TYPES

Although the overwhelming majority of aircraft are fitted with conventional pneumatic tires, occasionally a different type of gear is more suitable. This is true in the case of the light helicopter, where a skid-type gear is found to be superior. In this study, several gear types were considered for the Heavy Lift Helicopter including skids, skis, tracks, folding-tires and conventional pneumatic tires. Selection of the configurations to be studied further was based on the missions analysis and on operational concepts as discussed below.

Skids

An aircraft the size of the HLH with an empty weight approaching 40,000 pounds must have the capability of being moved, for maintenance, on hard surfaces without the necessity of starting the engines. It must also be capable of performing running takeoffs and landings under certain conditions, such as for a ferry mission. For these reasons, some ground mobility is necessary for the HLH; the skid gear does not fulfill this requirement.

Skis

Fixed-penetration wheel-skis have been used successfully on many helicopters. In most instances they are designed for operation from snow, and the ground contact pressures vary from 1-1/2 to 5 psi. Such skis have been used for operations from soft unprepared terrain, particularly in parts of Alaska where landings and takeoffs from muskeg are especially

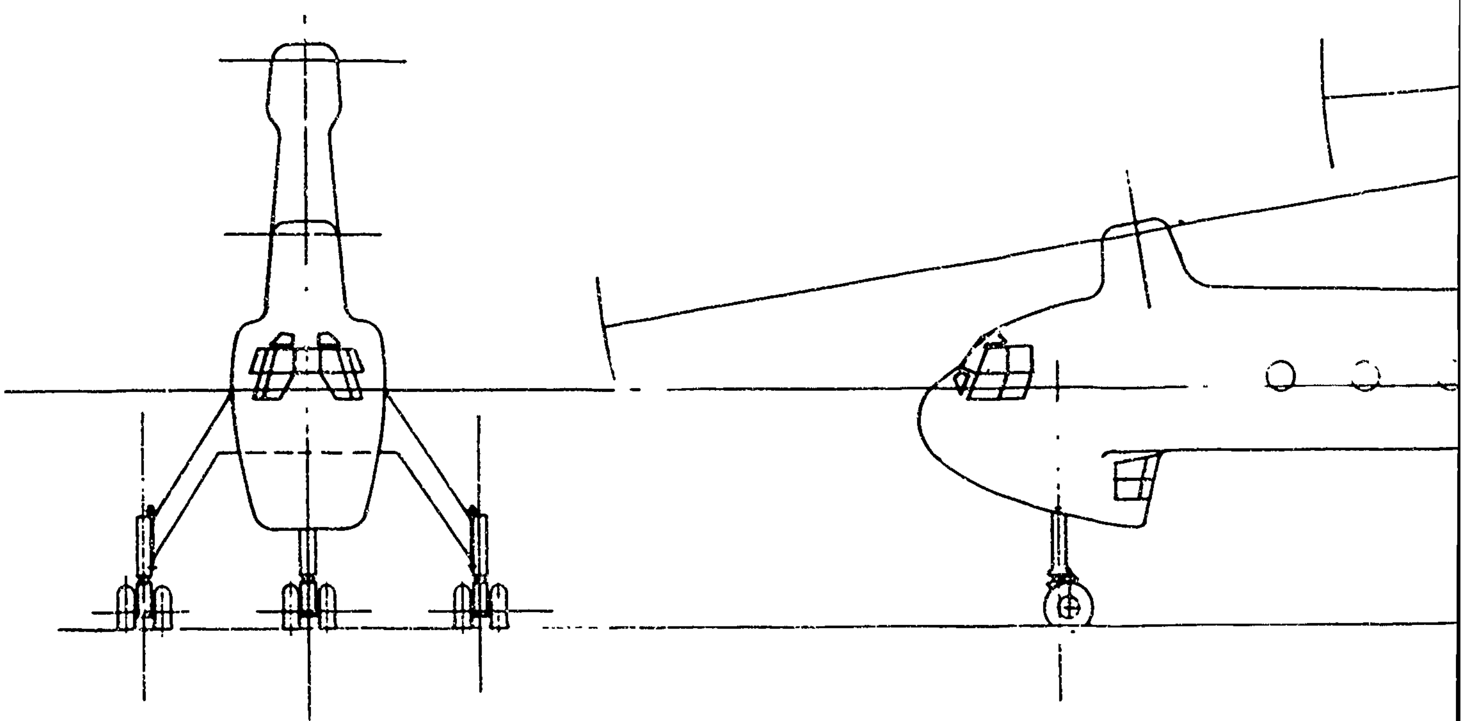
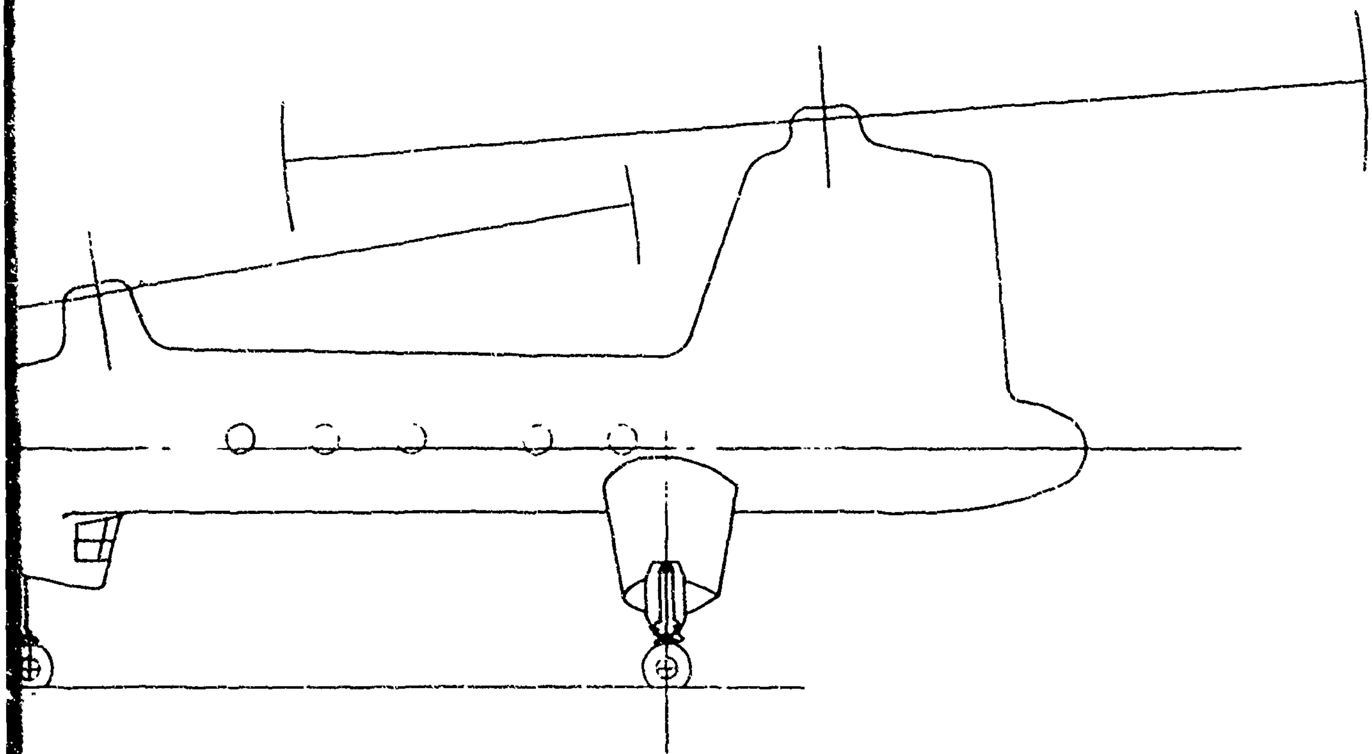


FIGURE 8. CRANE CONFIGURATION - TWIN WHEELS, 45-INCH DIAMETER, 100 PSI



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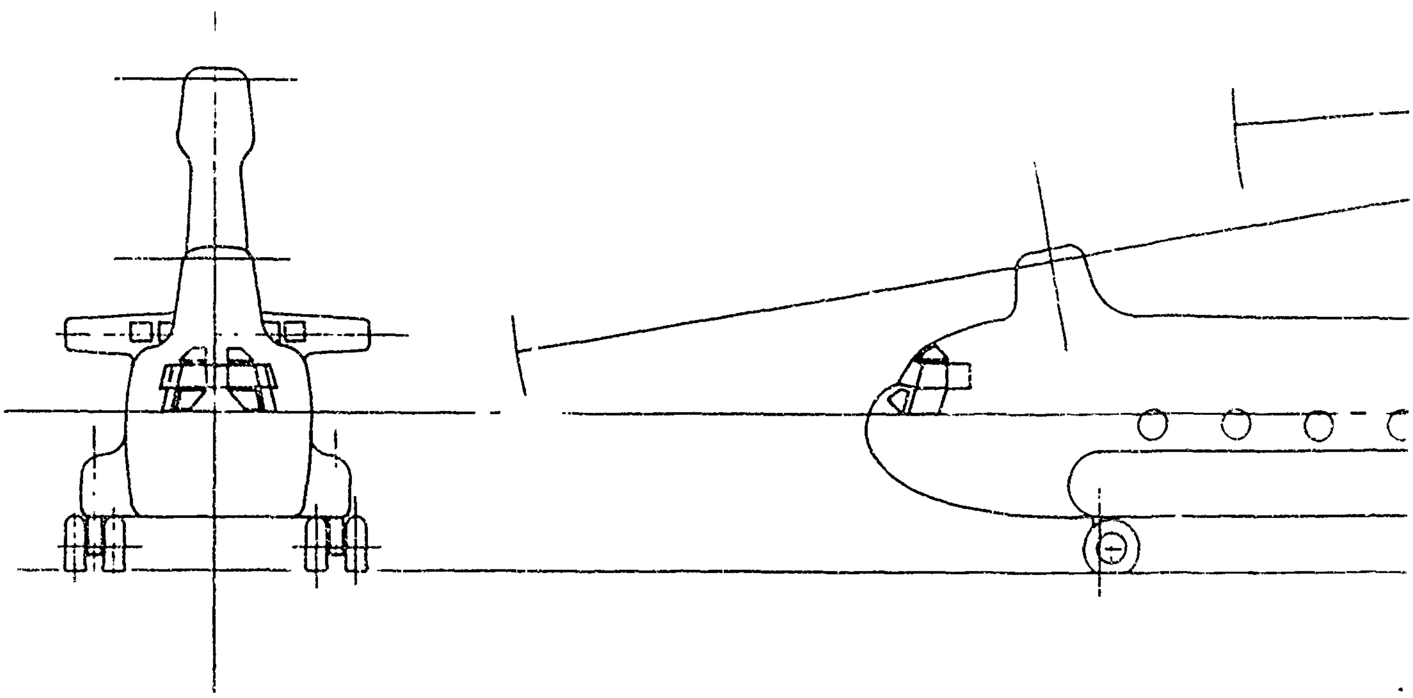
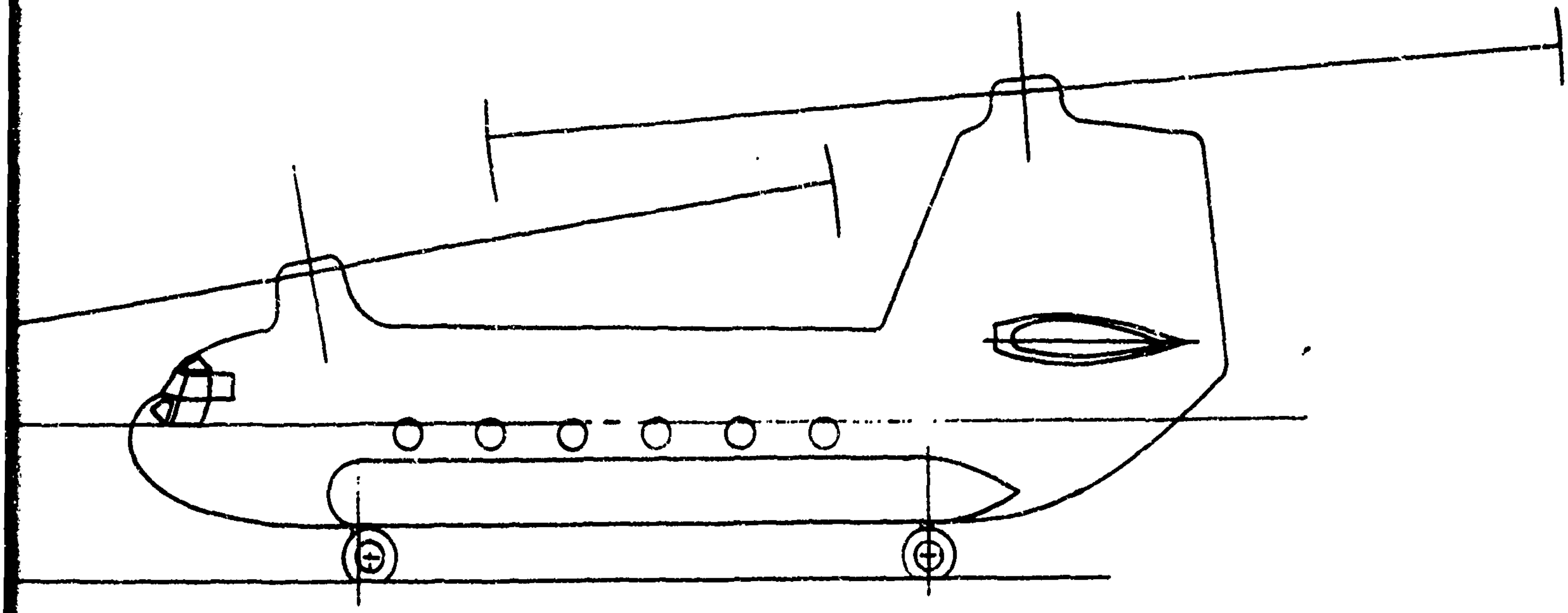


FIGURE 9. TRANSPORT CONFIGURATION - TWIN WHEELS, 52-INCH DIAMETER, 50 PSI



WHEELS,

2

hazardous, due to the great variation in soil bearing strength over very small areas. In a study of high-flotation landing gear for the CH-46A (Reference 4), Vertol Division of Boeing concluded that, for operation of that aircraft in most soft soils, a ground contact pressure of 12 psi offered the best compromise between flotation, weight, and aerodynamic drag. The wheel-ski does offer the best flotation characteristics for operation in very soft soils where running landings, take-offs, and other ground maneuvering are not required.

Assessment of the ski weight for a given application is difficult without detail design of the installation. Data are available, however, for the snow-skis designed for the CH-47. These snow skis, with a ground contact pressure of 2 psi, have a total weight of approximately 2.5 percent of the aircraft gross weight. This weight does not vary simply with contact area, since a major portion of the weight is made up of fittings, rigging devices, etc.

Ski-type surfaces may sometimes be fitted to a landing gear with only a small penalty in weight. Such is the case with a twin-tandem wheel arrangement, since the ski surface may be placed between the wheels and supported by the bogie beam.

Tracks

Experience to date with track-type landing gear has been largely unsuccessful, primarily because of complexity, weight, and difficulty of maintaining sufficient belt tension. While studying high-flotation landing gear for the CH-46A, the Vertol Division of Boeing investigated a new track gear concept called the Cushman track. This concept is simple, light, and self-compensating for belt tension. Model and prototype testing of this gear is currently being performed, and indications of its potential can be expected in the near future. This type of landing gear is most suitable for the assault type of V/STOL aircraft, where running landings and takeoffs in soft soil are required. Missions analysis shows that this type of operation is not required of the HLH; for this reason, track-type gear was not considered in this study.

Folding Tires

The primary reason for investigation of folding tires by at least two major companies (Fairchild Aircraft and B.F. Goodrich) is the need to minimize stowage volume in retractable landing

gear or to minimize aerodynamic drag in fixed gear.

The Fairchild folding tire, developed with the aid of Army funding, had very high flotation as a result of extremely low inflation pressures. It had the characteristic of being folded in flight and stowed in a wheel well of conventional proportions. More recently, B.F. Goodrich in conjunction with the USAF have developed a different concept in which tires of normal size, construction, and inflation pressure are folded into a much smaller wheel well.

Missions flown by the HLH are primarily of short duration with high-drag external loads; this means that the advantages of reduced landing gear drag resulting from gear retraction or reduction in tire size are outweighted by system complexity. For this reason, these tires were not considered in this study.

Pneumatic Tires

In order to allow complete freedom in choice of tire sizes for the design study, it was found expedient to reduce the tire characteristics to two parametric equations: one for size and the other for weight. The size equation was developed in a similar way to those described in Reference 12 with the exception that the tire fineness ratio (C=D/b) was included. The basic equation describes the footprint area nondimensionalized by D^2 as follows:

$$\frac{A}{D^2} = F \frac{\pi \delta}{C^2} \sqrt{(C-\delta) \quad (1-\delta)} \tag{5}$$

where

$C = D/b$, the tire fineness ratio

$\delta = \Delta/b$, the deflection delta nondimensionalized by tire section width b

F = correction factor for the type of tire, derived empirically.

NOTE: The nondimensional deflection parameter, δ, should not be confused with the normal Tire and Rim Association (T&RA) description of deflection, which is expressed as a percentage of the tire section height, measured from the wheel flange. The symbol δ was chosen to represent the deflection in the above equation because it was felt that

it would lead to better correlation, since it is more indicative of tire stresses. Correlation between δ and T&RA deflection was established in order to rate correctly the tires selected for the study.

Type III low-pressure and Type VII extra-high-pressure tire configurations were selected as a basis for the study since they are the two most commonly used types and span the inflation pressure spectrum from 20 to 350 psi. Analysis of a large number of tires was performed in order to determine the basic characteristics of these tires. Data were taken from the Goodyear Tire catalog.

A summary of the findings is included in Table VIII.

TABLE VIII. TIRE BASIC CHARACTERISTICS

Tire Type	III	VII
Inflation Pressure Range (psi)	20 - 165	55 - 360
Dia/Width Range (Approx)	2.4/3.5	3/5
Typical D/b	2.8	3.66
MIL-T-5041D Deflection Range - Fixed-Wing A/c (%)	35+1, -4	32+3, -4
Footprint Area Correction Factor - F (Refer to Equation 4)	0.83	0.79

Preliminary analysis of the HLH landing gear requirements indicated that tire pressures in excess of 150 psi would be undesirable; therefore, on this basis, the Type VII tire would be unnecessary. Additional consideration showed that the Type VII tire would be considerably larger in diameter and heavier than the Type III for equal footprint area. For these reasons, the detail analysis of design concepts was performed with Type III tires.

The allowable maximum deflection for helicopter tires is greater than for fixed-wing aircraft, primarily because of the reduced rolling distance, which minimizes heat buildup, and the reduced landing load factors, which lessen the possibility of bottoming the tire on the wheel rim. Helicopter tires are normally rated in the following manner. Allowable increases are 1.67 times the rated load and 1.5 times the rated inflation pressure for fixed-wing aircraft applications. Maximum permissible inflation pressure for tires used on helicopters is 1.8 times that used for fixed-wing aircraft.

For the purpose of this study, since it was not concerned with uprating existing tire capacities, the deflection and pressure adjustments were separated. This was done because the size of the tire is primarily a function of deflection for a given pressure, and the change in pressure rating as described above primarily affects the ply rating of the tire or, more importantly for this study, the tire weight. The deflection chosen for this study is 40 percent, which corresponds to a δ of 0.32 for the Type III tire.

The equation which determines tire weight was established by fitting a curve to a family of data by the least-squares method. The equation for aircraft-rated tires was then adjusted to correspond to a pressure increase factor of 1.5 for helicopter usage. This equation for helicopter-rated Type III tires with $D/b = 2.8$ is

$$W_T = \frac{D^{2.66} \; P^{.381}}{1319} \qquad (6)$$

The equation for tire size and weight was used to construct the nomograph shown in Figure 10.

Wheels

Wheel weights to correspond to selected tires were established in a similar manner to the tire weight trends. Based on a family of data on helicopter-rated forged aluminum aircraft wheels, a series of plots was made to establish the sensitive parameters. The results showed a strong correlation between weight, tire outside diameter, and tire diameter/width ratio. It is interesting to note that the correlation was very good with tire outer diameter but very poor with wheel outer diameter.

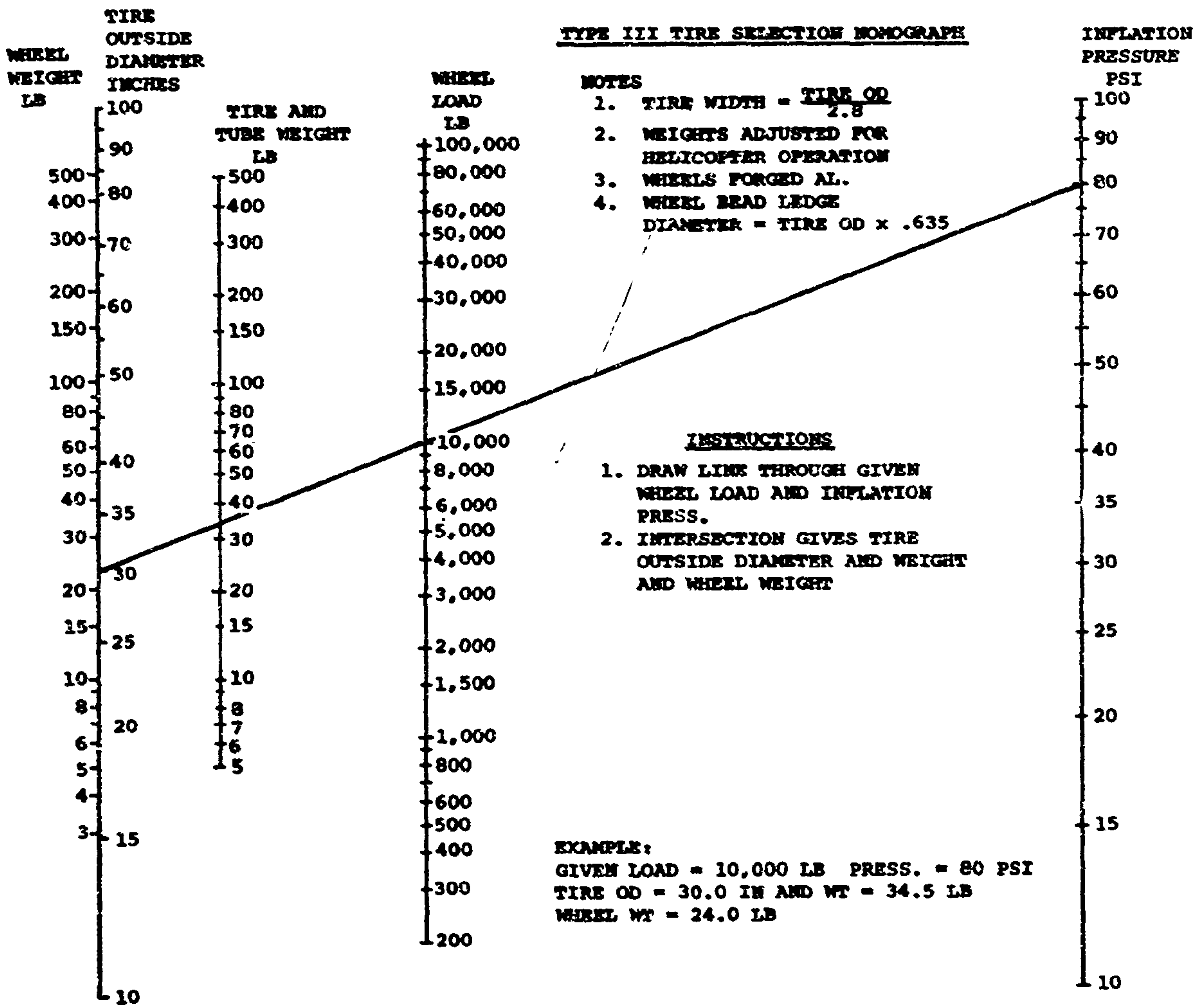


FIGURE 10. TIRE SELECTION NOMOGRAPH

[illegible]
which were also plotted on Figure [illegible]

$$W_w = \frac{D^{2.98} \; C^{1.92}}{7880} \tag{7}$$

and for C = 2.8 this equation reduces to

$$W_w = \frac{D^{2.98}}{1091} \tag{8}$$

WEIGHT SUMMARY

The results of the detailed analysis of shock strut, axle, and bogie beam assemblies are plotted in Figure 11. It should be noted that in some instances the full strength of the 280-ksi steel could not be used to advantage because of limiting diameter/thickness ratios in the shock strut tubes. Use of high-strength aluminum forgings could possibly produce lighter assemblies under these conditions, but it was considered that the accuracy of the analysis is sufficient for the purposes of this report.

Brake weight was not included in this analysis since there would be only a small change between the various configurations, kinetic energy being constant.

Backup structure was likewise neglected because, although it may change somewhat between the various configurations, it is not possible to estimate it with any accuracy unless detail structural design studies are performed.

No attempt should be made to compare the weight of the transport configuration's quadricycle gear with that of the crane's tricycle gear without including the weight of the backup structure. Such a comparison was not the object of this study.

The final weight breakdown is included in Table IX and summarized in Figures 12 and 13. It is apparent from these curves that there is a significant reduction in gear weight with an increase in the number of wheels, particularly at low inflation pressures.

Drag estimates were made [illegible]
landing gear type. Based on these estimates [illegible]
maximum speed and range were computed.

Maximum speed deltas are referred to the normal-rated-power speeds (also to the transmission limit of 12,000 HP) of 163 knots for the transport and 152 knots for the crane at the design gross weight at sea level standard. The effect of increased drag on range is referred to ferry range at optimum altitudes to 10,000 feet. Maximum ferry range is 1755 nautical miles for the transport and 1645 nautical miles for the crane. Both aircraft have three-bladed, 43-foot-radius rotors, and four T55-L-11 engines with a maximum installed power rating of 3750 SHP each at sea level standard.

The results of this analysis are presented in Figure 14. Linear extrapolations were made based on the data points, and although this may not be completely accurate, the resulting error is small since the change in total performance itself is small.

The cleanest landing gear configuration for the crane is a twin-tandem arrangement with a wheel diameter of 20 inches and inflation pressure of 150 psi. For the basic crane configuration, this arrangement reduces the drag and increases the ferry range by 105 nautical miles and V_{max} by 75 knots. The worst configuration has dual wheels of 69-inch diameter each, 25 psi inflation pressure; this decreases ferry range by 167 nautical miles and V_{max} by 8.5 knots.

All landing gear configurations studies on the transport show decrements in performance when referred to the basic aircraft, since the original concept, as defined in Reference 15, had a tricycle gear arrangement. The best quadricycle gear in this study has single tires of 35-inch diameter and inflation pressure of 150 psi. The penalty to ferry range amounts to 20 nautical miles and maximum speed decreases by 2.2 knots. The worst transport configuration shown has single tires of 85-inch diameter, 25 psi inflation pressure. This arrangement decreases range and V_{max} by 117 nautical miles and 8.5 knots respectively.

TABLE IX. WEIGHT SUMMARY

Wheel Arrangement	Tire Load (Lb.)	Outside Diameter (In.)	Inflation Pressure (Psi)	Weight Per Tire (Lb)	Weight Per Wheel (Lb)	Wt Per Shock Strut Assy (Lb)	Total Landing Gear Weight (Lb)
		TRANSPORT CONFIGURATION					
Single	25621	104	17.4	490	940	820	9000
		79	29	295	410	721	5704
		60	51	170	180	640	3960
		51	69	130	115	590	3340
		35	150	64	36	497	2388
Twin	12816	68	19.6	170	270	560	5840
		52	34.5	105	120	498	3792
		0	58.	64	54	445	2724
		34	81	46	33	416	2296
		25	150	26	12.5	385	1848
Twin-Tandem	6408	45.5	22.5	64	80	548	4496
		35	38	39	36	519	3276
		26	67.5	22	15	492	2560
		23	85	17.5	11	478	2368
		17.5	150	10	4.5	460	2072
		CRANE CONFIGURATION					
Single	32707	120	16.5	700	1400	935	9105
		91	29	430	620	861	5733
		69	50	260	280	790	3990
		59	69	190	175	750	3345
		40	150	90	53	655	2394
Twin	16354	78	19.4	250	400	795	6285
		60	33	150	185	684	4062
		45	59	87	76	594	2766
		39	78	68	50	540	2328
		28	150	36	18	470	1734
Twin-Tandem	8177	52	22	89	120	667	4509
		40	37.5	55	54	646	3246
		30	65.5	31	24	620	2520
		26	88	24	15	605	2283
		20	150	14	6.5	590	2016

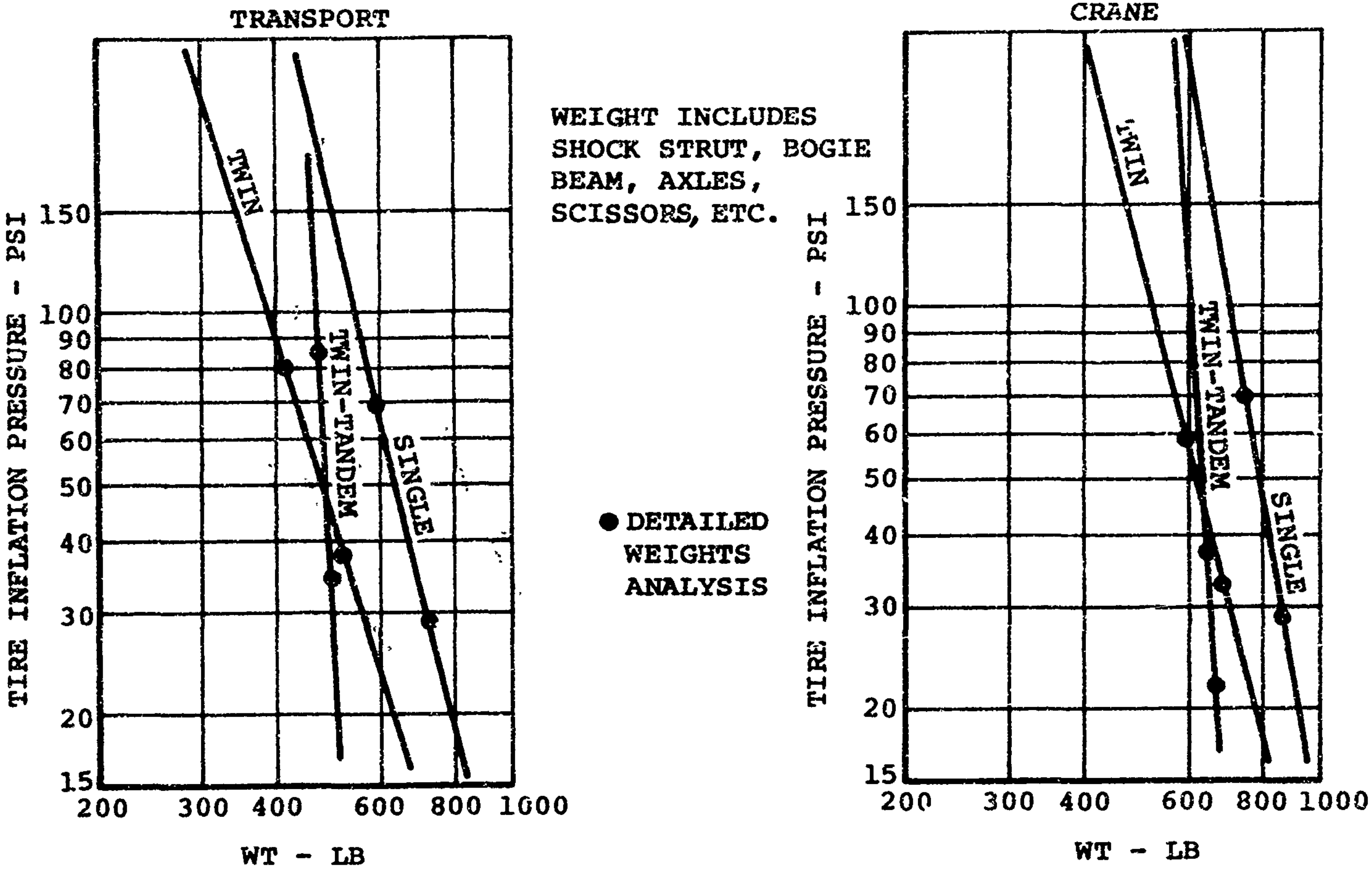


FIGURE 11. SHOCK STRUT ASSEMBLY WEIGHTS PER GEAR

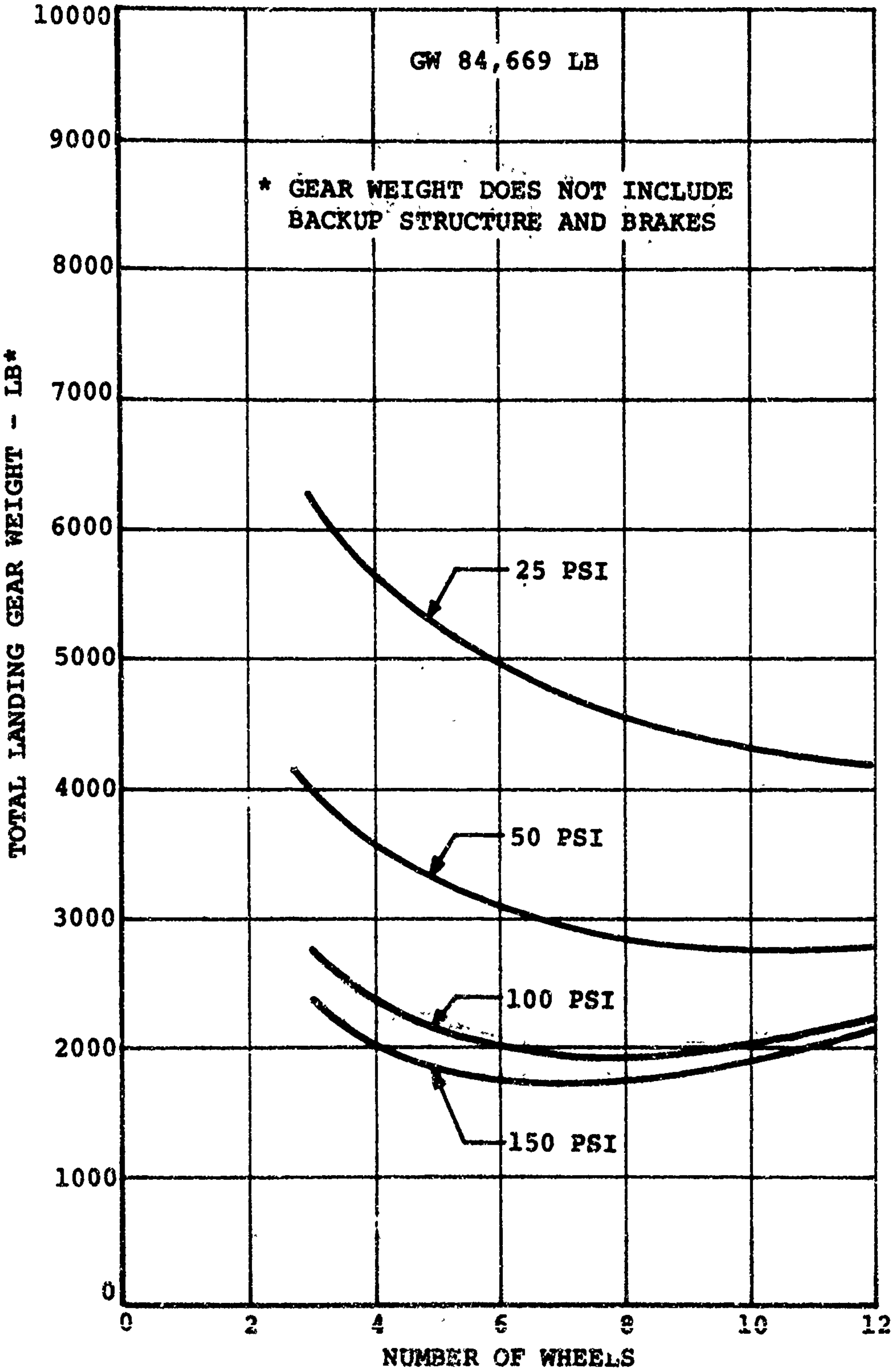


FIGURE 12. TOTAL GEAR WEIGHT - CRANE CONFIGURATION

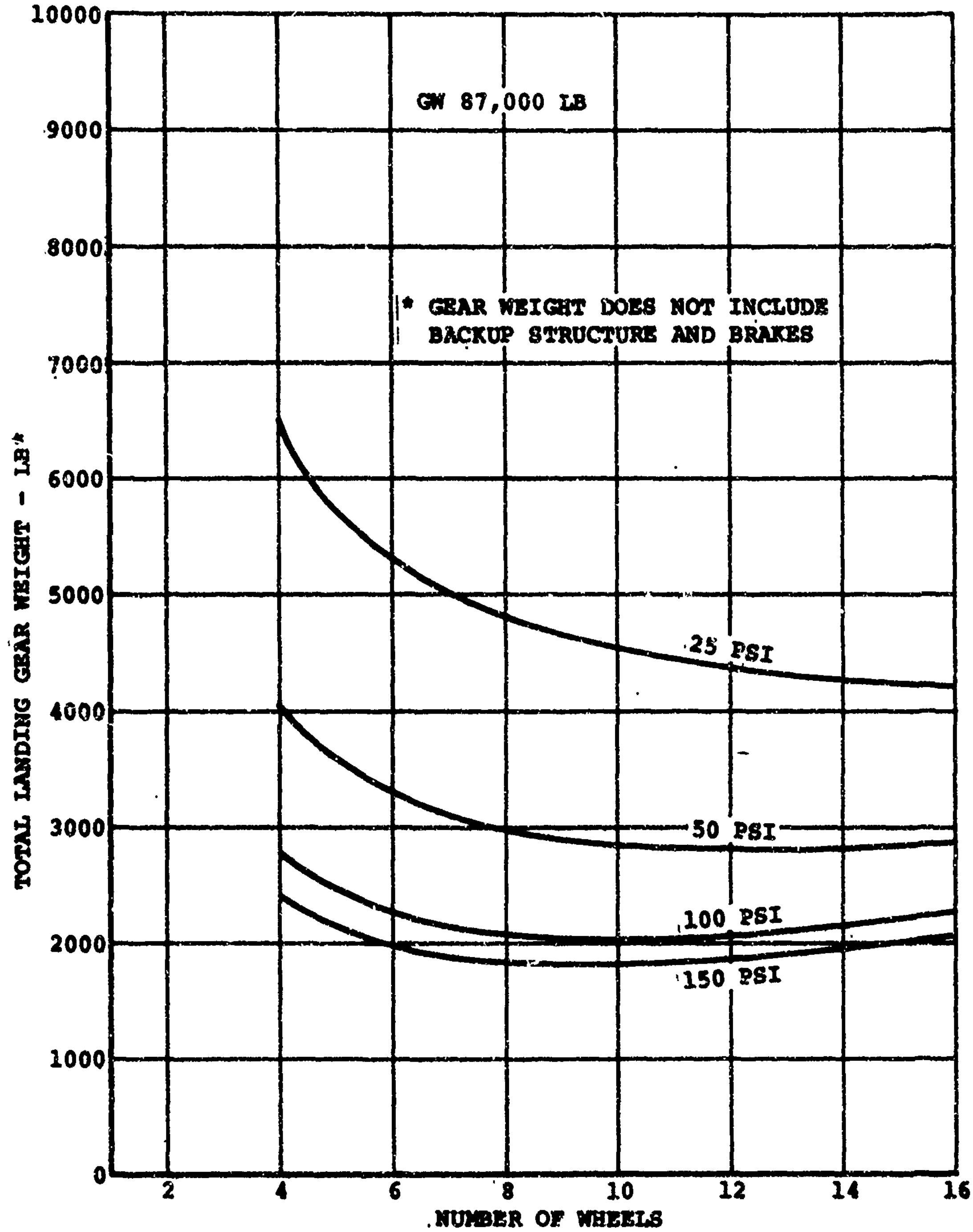


FIGURE 13. TOTAL GEAR WEIGHT - TRANSPORT CONFIGURATION

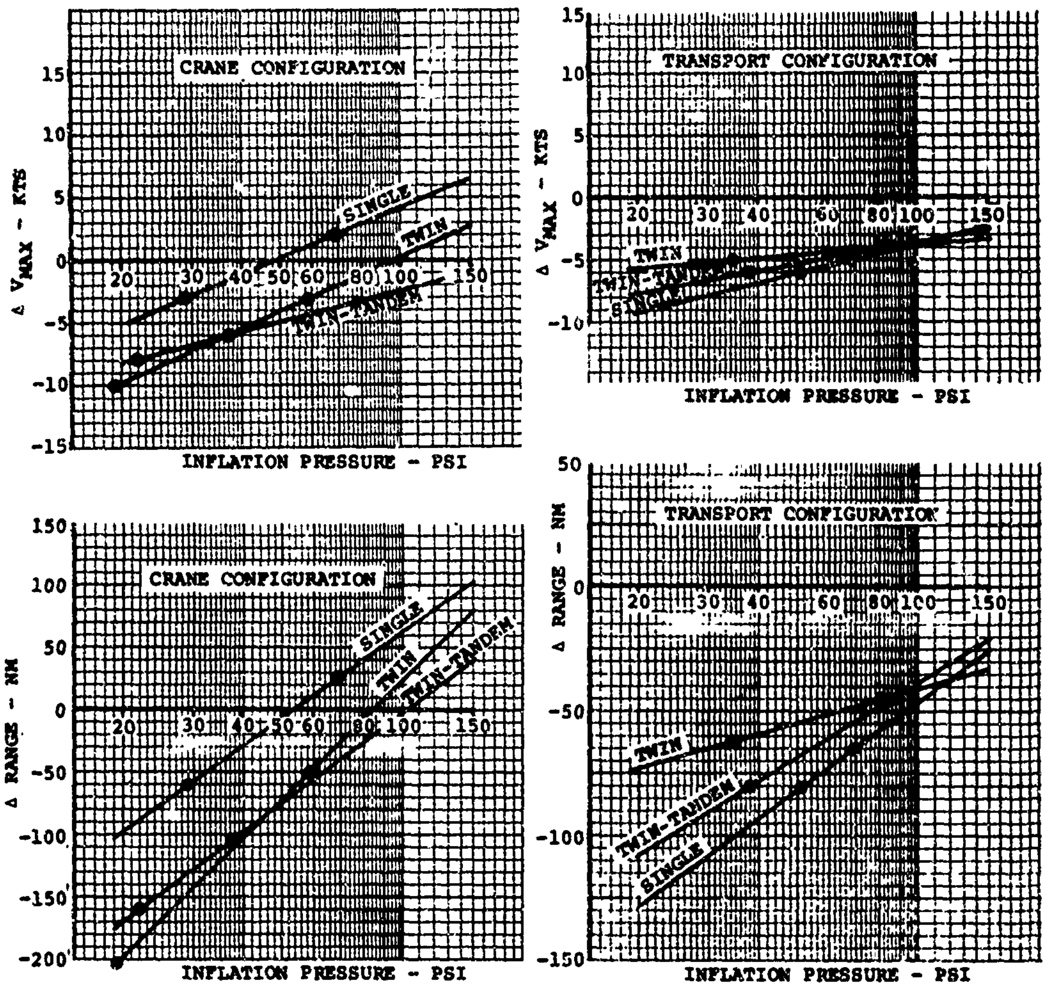


FIGURE 14. EFFECT OF LANDING GEAR DRAG ON PERFORMANCE (BASED ON HLH ROTOR CONFIGURATION STUDY)

(U) HEAVY LIFT HELICOPTER FLOTATION CRITERIA

The HLH missions analysis yields a broad description of the operational characteristics which form the basis for determination of the flotation requirements of the landing gear. The single most important characteristic is the definition of the HLH as a utility machine designed primarily to carry outsized loads over comparatively short radii. With the exception of the ship-to-shore mission, there are no highly repetitive missions such as would be the case if the HLH formed a link in an air line of communication.

The overwhelming percentage of missions are flown with external cargo because of both the size of some loads and the desirability of spending minimum time in acquiring and depositing loads. The majority of these loads must be acquired in hover, the exceptions being special purpose "people pods" (which were not used in the missions analyses) and those loads which are suitable for straddle pickup.

It is apparent, then, that although these conclusions indicate that the vast majority of the missions are the crane type, a transport configuration may be equally suitable. Tradeoff studies on the other parameters affecting choice of configuration are not the concern of this report except for one point. This is that if the helicopter is configured primarily to carry external loads and the majority of loads are acquired in hover, then it is reasonable to assume that the tire inflation pressures may be reduced from that level indicated by maximum design gross weight. This would not, however, be a sound practice for a transport configuration where internal and external loading may be used on alternate missions.

For the above reasons it was decided to analyze the transport configuration for transport-type missions (not covered by the mission analysis) at maximum design gross weight under all conditions. The crane configuration was analyzed for maximum design gross weight operation on ZI and TO rear and support-area fields. Operations from TO forward-area fields and unprepared soil were made at basic weight, with fuel for a three-hour mission.

OPERATIONS FROM PREPARED SURFACES

If the great utility of the HLH is to be realized, it must be capable of operating from all Zone of Interior and Theater of Operations airfields, roads, parking lots, and hardstands.

Analysis of ZI flotation criteria indicates that only the single-wheel gear of the crane configuration is critical at maximum gross weight. In this case the maximum allowable tire inflation pressure is 45 psi.

Successful operation from roads and parking lots requires (according to WES) tire pressures preferably less than 100 psi, with 150 psi as an absolute maximum. This roughly corresponds to heavy truck practice. It should be noted that the HLH is a very heavy vehicle, and it is unreasonable to expect it to operate from areas such as very light grade parking lots without damaging the surface.

It has previously been stated that, in order to define the required number of coverages expected from an aircraft operating from a TO airfield, it is necessary to establish the cycle rate both for the aircraft in question and for other aircraft using the field during the operation. The foregoing missions analysis indicated that the HLH will not inflict heavy cycle rates on TO support-area fields -- these being more critical than rear-area fields. The actual maximum weekly cycle rate encountered was 60, or 240 cycles in one month - the expected life of a support-area field. Due to the fact that few landings will be made for each cycle and due also to the higher pass-to-coverage ratio which should be afforded the helicopter, the resultant coverage rate is very low. In the event that the actual coverage rate cannot be determined, WES recommended that 200 be the number used for support-area fields. The results of the rear- and support-area flotation analysis for both crane and transport configurations are shown in Figures 15 and 16.

For the crane configuration, the 200 coverage support area requirement is somewhat more severe than either 40 coverages forward area field or D/3 sinkage in cone index 30 soil. The additional weight penalty over a gear designed to these criteria is approximately 200 pounds. This is shown in Figure 17, which is a graph of total landing gear weight as a function of tire inflation pressure and number of wheels, with cross plots of the various flotation criteria discussed

in this section. These data are summarized in Table X.

In the case of the transport, the 200 coverage support area field requirement is somewhat less severe than the 40 coverage forward area field or D/3 sinkage in CI 30 soil. Configuration would be chosen because of missions in addition to those described in the HLH draft QMR, such as an air-line-of-communication logistics function; in this case, maximum-gross-weight landings must be made, and the criteria for the 200-coverage support-area field must be assumed correct. The weight-pressure-flotation characteristics of the transport configuration are shown in Figure 18 and summarized in Table XI.

Problems concerned with definition of coverage rate on TO forward-area fields for the crane configuration are similar to those for the support-area field described above; namely, few landings per operation and uncertain pass-to-coverage ratio. The maximum weekly cycle rate from the missions analysis is 78, or 234 in three weeks - the expected life of a forward-area field. The WES-recommended coverage for forward area fields where the actual allotted coverage is not known is 40.

OPERATIONS FROM UNPREPARED TERRAIN

The flotation of the landing gear configurations discussed in the landing gear flotation section was analyzed by the ATAC methods. The results of this analysis are presented as curves of sinkage as a function of soil modulus in fine-grained soil (see Figures 19 through 27). The line indicating the arbitrary sinkage limits of D/3 is cross plotted on these curves.

The motion resistance in sod of these configurations (although of little consequence to this analysis, for reasons previously stated) is included for the sake of completeness in Figures 28, 29 and 30.

To quantitatively assess the tradeoff between landing gear flotation in soft soil and mission effectiveness, three degrees of soft soil were chosen as separate criteria for operation in unprepared terrain; they are shown in Table XI.

TABLE X. LIMITING SOIL STRENGTHS

Cone Index	Approximate Equivalent k (n=0.2)	CBR	Description of Soil Strength
60	30	1.5	Multiple operations of most medium tanks, tractors with high contact pressures, all-wheel-drive trucks with low contact pressures. Limited operation of most all-wheel-drive trucks and heavy tanks.
30	15	0.75	Multiple operations of engineer and high-speed tractors with wide tracks and low contact pressures. Limited operation of tractors with average contact pressures and tanks with low contact pressures.
10	5	0.25	Marginal mobility of special amphibious type vehicles. Marginal mobility of foot soldiers.

Lines indicating the limiting D/3 sinkage criteria for each of the soil strengths are shown cross plotted on Figures 17 and 18.

The CI-30 minimum soil strength corresponds to the lower limit for all mission-constrained soil strengths. That is to say, if the aircraft is capable of operating in soil with CI-30, then it can perform all those missions in which the minimum soil strength is determined by the type of operation. This covers all the unsurfaced soil missions in the Bangkok area and all but four (representing 1 percent) of the missions in the Cam Rahn Bay area.

D/3 sinkage criteria for CI-30 soil show that the required inflation pressure reduces with an increased number of wheels. For the minimum-weight (multi-wheel) gear in both crane and transport configurations, the CI-30 criteria closely match and

are a little more severe than the forward-area 40-coverage criteria. There is, therefore, a penalty associated with flotation criteria requiring operation from CI-30 soil (crane 50 pounds, transport 150 pounds), for a gear designed to the TO airfield criteria described above.

The constraints due to operation on prepared airfields ensure adequate flotation to cover all missions in the Bangkok, Bremerhaven, and Oakland areas. The probability of mission completion on the basis of landing gear flotation is 100 percent.

In the Cam Rahn Bay area, 1 percent of the missions could be to areas with soil strengths below CI-30. Assuming an even distribution of missions over the area, the probability of mission completion for those missions is equal to the percentage of the total area with soil strengths greater than CI-30. A soil strength spectrum for Southeast Asia is presented in a report entitled Marine Corps Logistic Systems Study (Reference 10). By using this spectrum, which relates the percentage of area to soil strength, it is apparent that approximately 97 percent of the area exceeds CI-30. Therefore, the total probability of mission completion for the Cam Rahn Bay area is 99.97 percent.

Operations into soil with CI-10 strength may be necessary for some missions such as recovery of downed aircraft. The characteristics of a wheel-type landing gear to satisfy the D/3 sinkage criteria in this soil are shown in Figures 17 and 18.

The weight increase for the crane multi-wheel landing gear is approximately 990 pounds or 1.15 percent of gross weight over that defined by CI-30 requirements. Reductions in maximum speed and range are 3.5 knots and 100 nautical miles, respectively.

Corresponding figures for the transport are 2580 pounds or 3.0 percent increase of gross weight, with reduction in speed and range of 1.2 knots and 20 nautical miles, respectively.

Since such missions into very soft soils represent only a small percentage of the total utilization, it would be beneficial to provide the additional flotation capability in the form of a field-installed kit. In this way, no weight and drag penalty would be imposed during normal missions. For the

type of missions performed in very soft soil, the addition of a ski to the normal landing gear would be the most efficient solution. In the discussion of ski-type landing gear in the landing gear configurations section, it was stated that the best ground pressure for a soft-soil-type ski is approximately 12 psi. Although no actual weight data could be found for a ski of this size, snow ski weights in the 2-to-3-psi-ground-pressure class amount to between 1.5 and 2.5 percent of gross weight. It is reasonable to assume, therefore, that 12-psi skis could be built for approximately 1 percent of gross weight (or landing weight, in the case of the crane). This would yield ski weights of 550 pounds for the crane and 870 pounds for the transport; in both cases, this is considerably less than the weight of the wheel-type landing gear with equivalent capability as described above.

The percentage of soils stronger than CI-10 in the Southeast Asia Theater, from Reference 10, is approximately 99 percent. This value applied to the 1 percent of missions in soil with random strength produces an overall probability of mission completion of 99.99 percent in the Cam Rahn Bay area for an aircraft with the capability of landing in soil with CI-10.

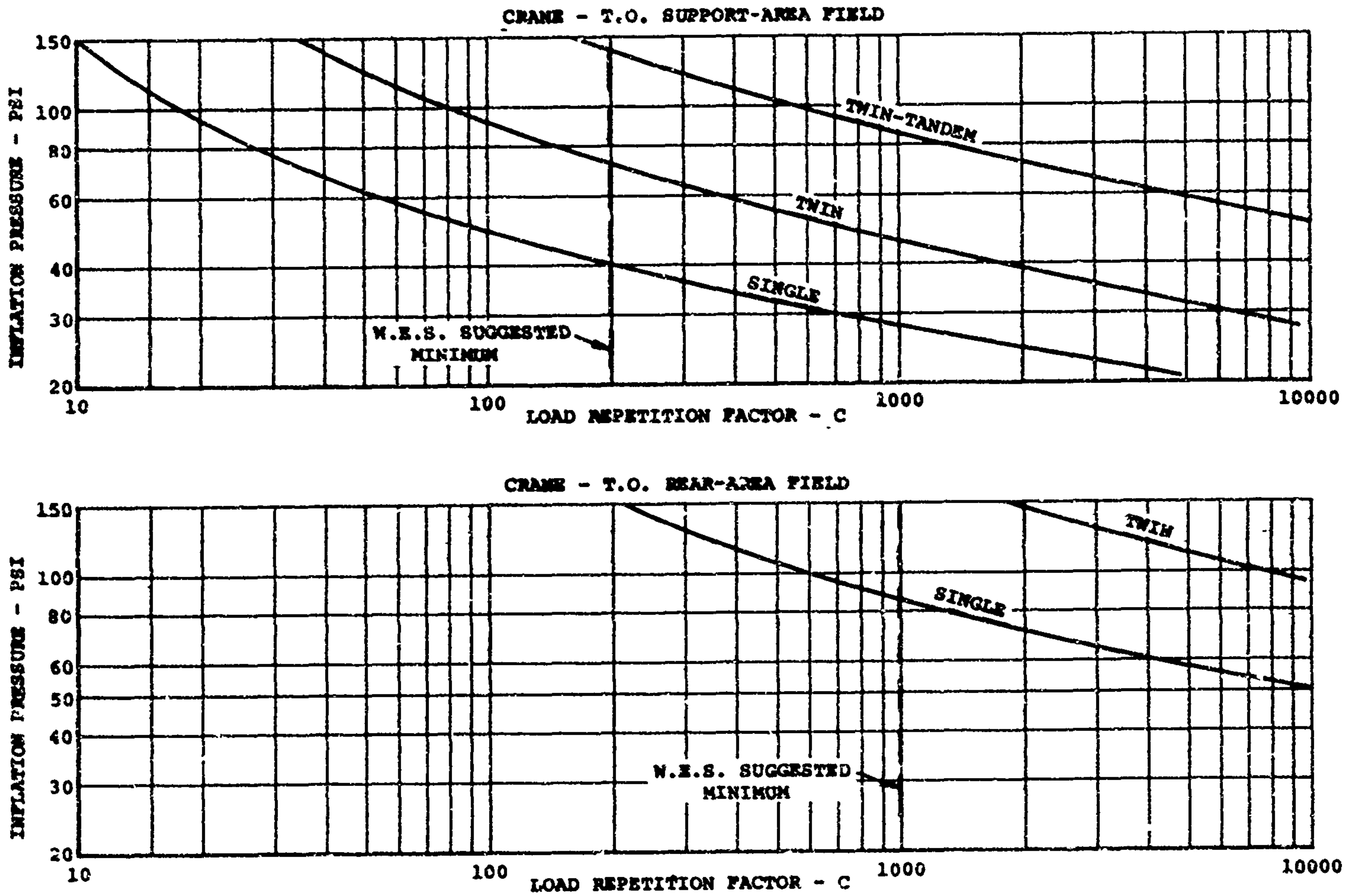


FIGURE 15. FLOTATION OF CRANE ON THEATER OF OPERATIONS REAR- AND SUPPORT-AREA FIELDS - GW 84,669 LB

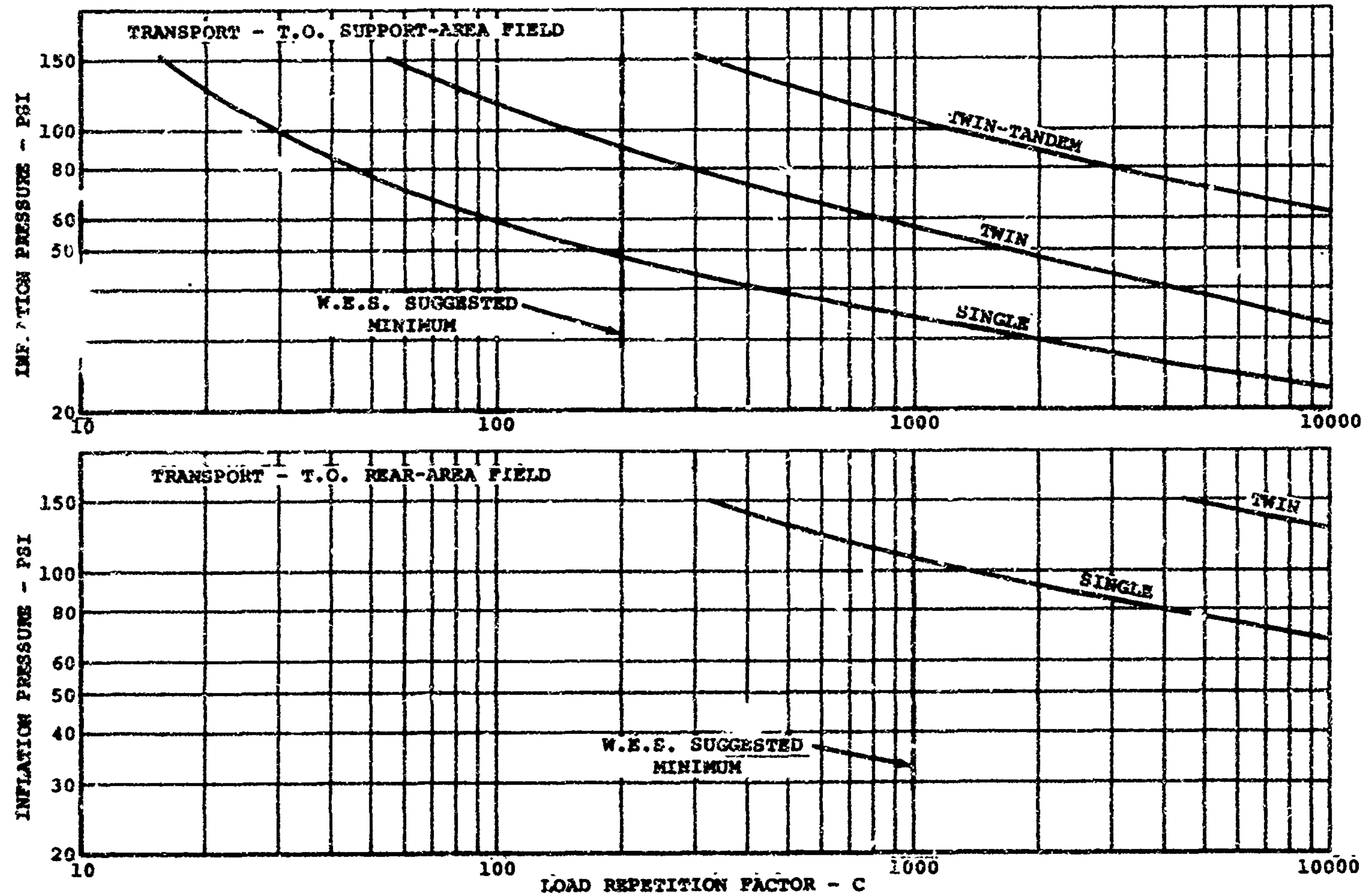


FIGURE 16. FLOTATION OF TRANSPORT ON THEATER OF OPERATIONS REAR- AND SUPPORT-AREA FIELDS - GW 87,000 LB

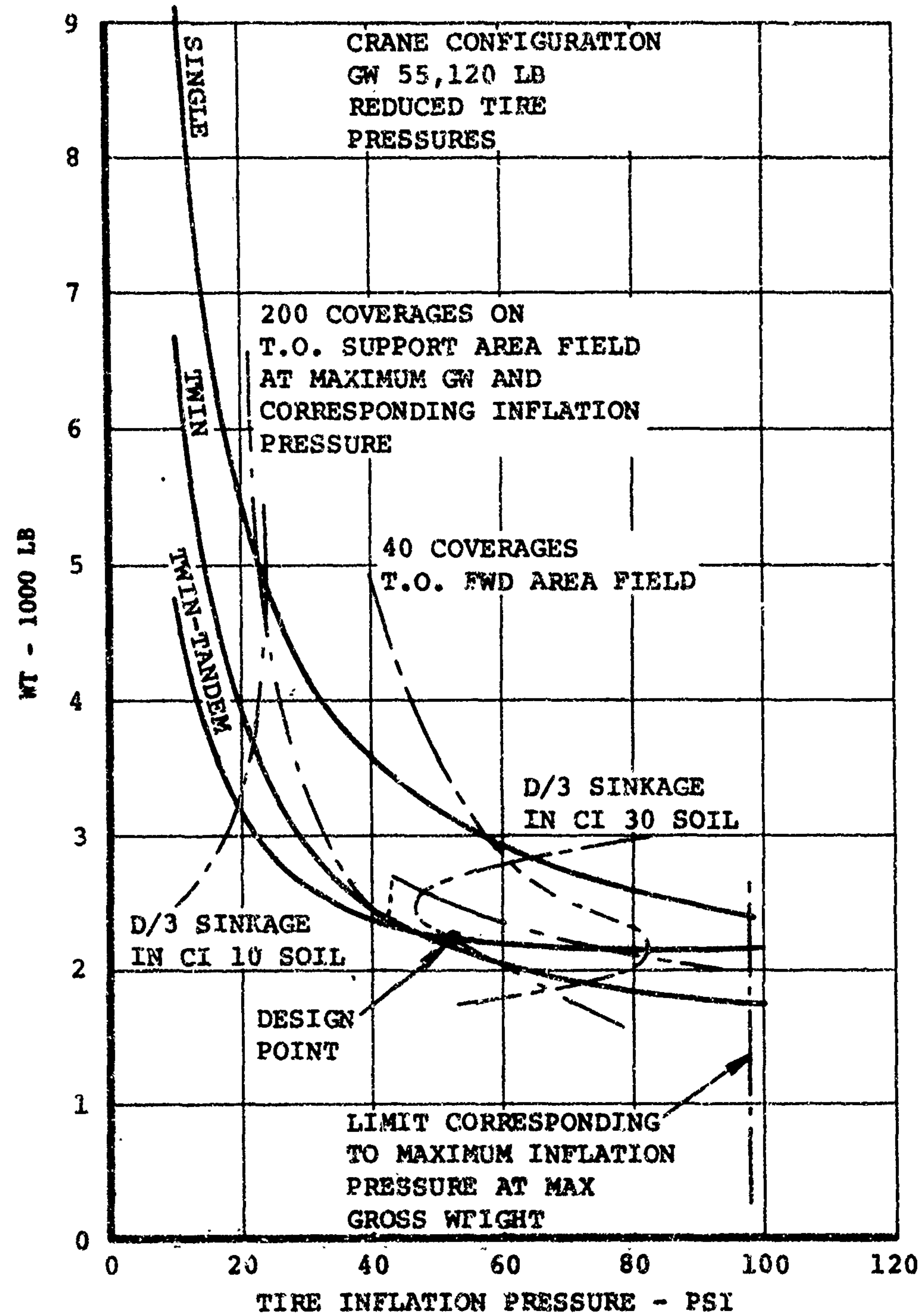


FIGURE 17. CRANE CONFIGURATION FLOTATION CRITERIA

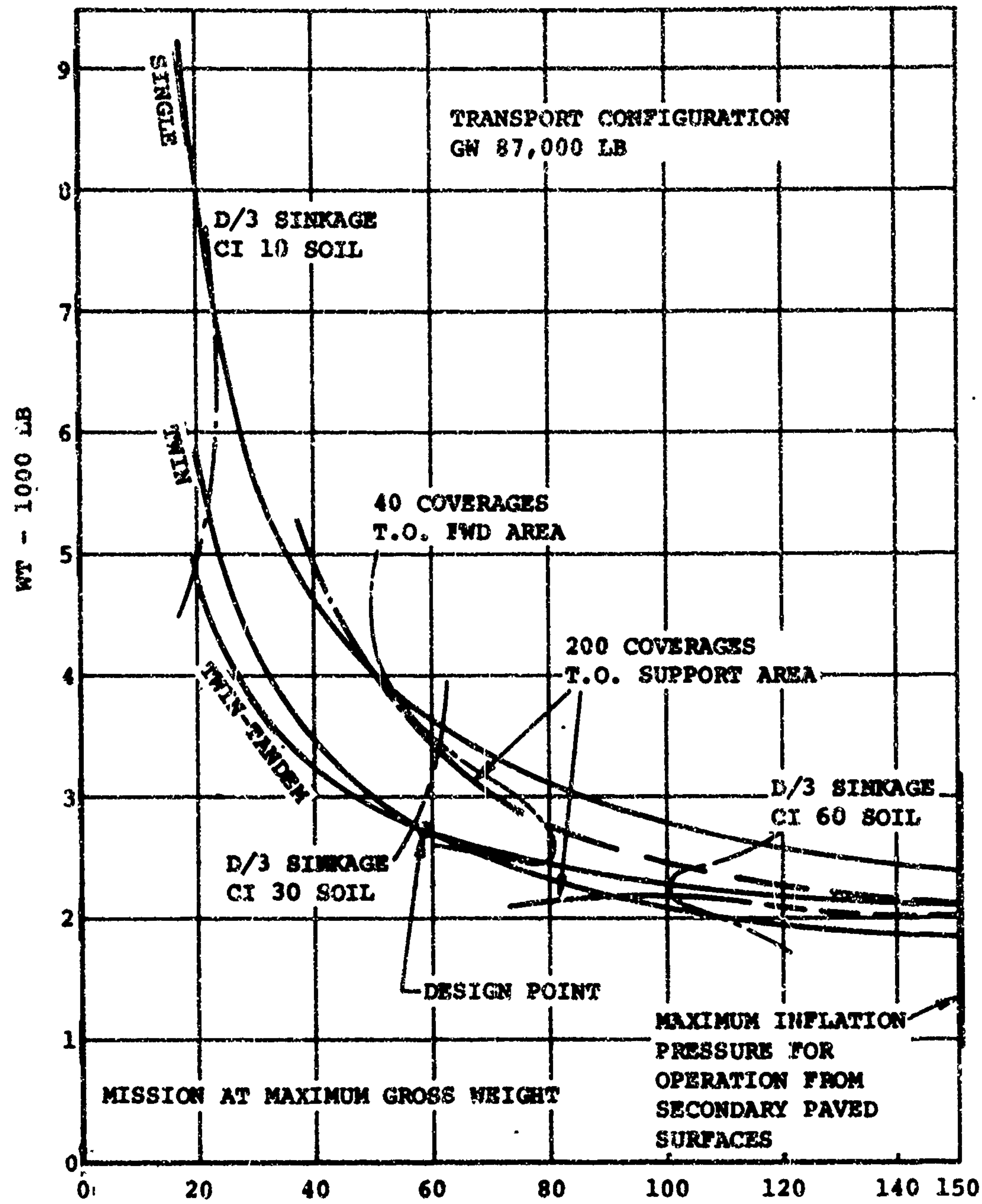


FIGURE 18. TRANSPORT CONFIGURATION FLOTATION CRITERIA

TABLE XI. WHEEL DIAMETER, INFLATION PRESSURE, AND TOTAL GEAR WEIGHT DEFINED BY FLOTATION CRITERIA

FLOTATION CRITERIA	SINGLE-WHEEL GEAR Transport	SINGLE-WHEEL GEAR Crane	TWIN-WHEEL GEAR Transport	TWIN-WHEEL GEAR Crane	TWIN-TANDEM-WHEEL GEAR Transport	TWIN-TANDEM-WHEEL GEAR Crane
Maximum Inflation Pressure 150 psi						
Wheel OD - inches	35	40	35	28	17.5	20
Inflation Pressure - psi	150	150	150	150	150	150
Total Gear Weight - lb	2388	2394	1848	1734	2072	2016
D/3 Sinkage in CI 60 Soil						
Wheel OD - inches	40	35	29	26	22	20
Inflation Pressure - psi	115	120*(184)	110	110*(169)	100	98*(150)
Total Gear Weight - lb	2600	---	2204	---	2250	---
D/3 Sinkage in CI 30 Soil						
Wheel OD - inches	54	49	40	36	29	27
Inflation Pressure - psi	62	64*(98)	59	59*(91)	54	52*(80)
Total Gear Weight - lb	3550	2830	2720	2050	2800	2230
D/3 Sinkage in CI 10 Soil						
Wheel OD - inches	88	78	65	59	48	44
Inflation Pressure - psi	23	24*(38)	22	22*(34)	20	19.5*(30)
Total Gear Weight - lb	7000	4820	5300	3680	4820	3220
40 Coverages - Theater of Operations Forward Area Field						
Wheel OD - inches	59	52	37.5	32.5	24	22
Inflation Pressure - psi	52	58*(89)	66	72*(111)	78	82*(126)
Total Gear Weight - lb	3950	2950	2550	1900	2450	2150
200 Coverages - Theater of Operations Support Area Field						
Wheel OD - inches	62	83	32	46	---	23
Inflation Pressure - psi	48	35	90	61	---	117
Total Gear Weight - lb	4150	5000	2170	2450	---	2150

*Inflation pressure corresponding to operation at the basic weight, plus 3 hours fuel at a gross weight of 55,128 pounds. The number in parentheses indicates the inflation pressure corresponding to operation at the weight used for sizing the gear, 84,669 pounds maximum gross weight.

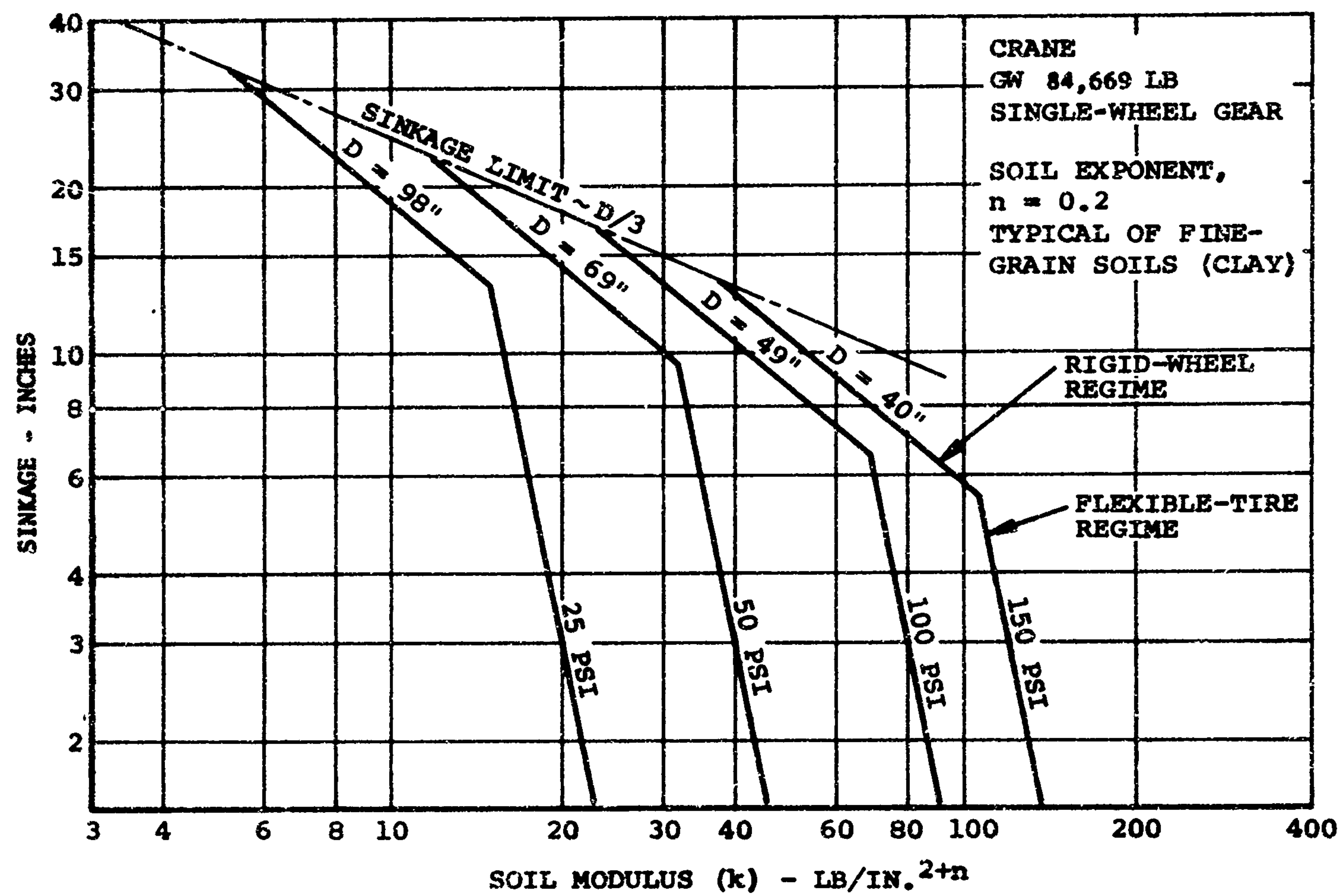


FIGURE 19. TIRE SINKAGE - SINGLE-WHEEL-GEAR CRANE (84,669 LB)

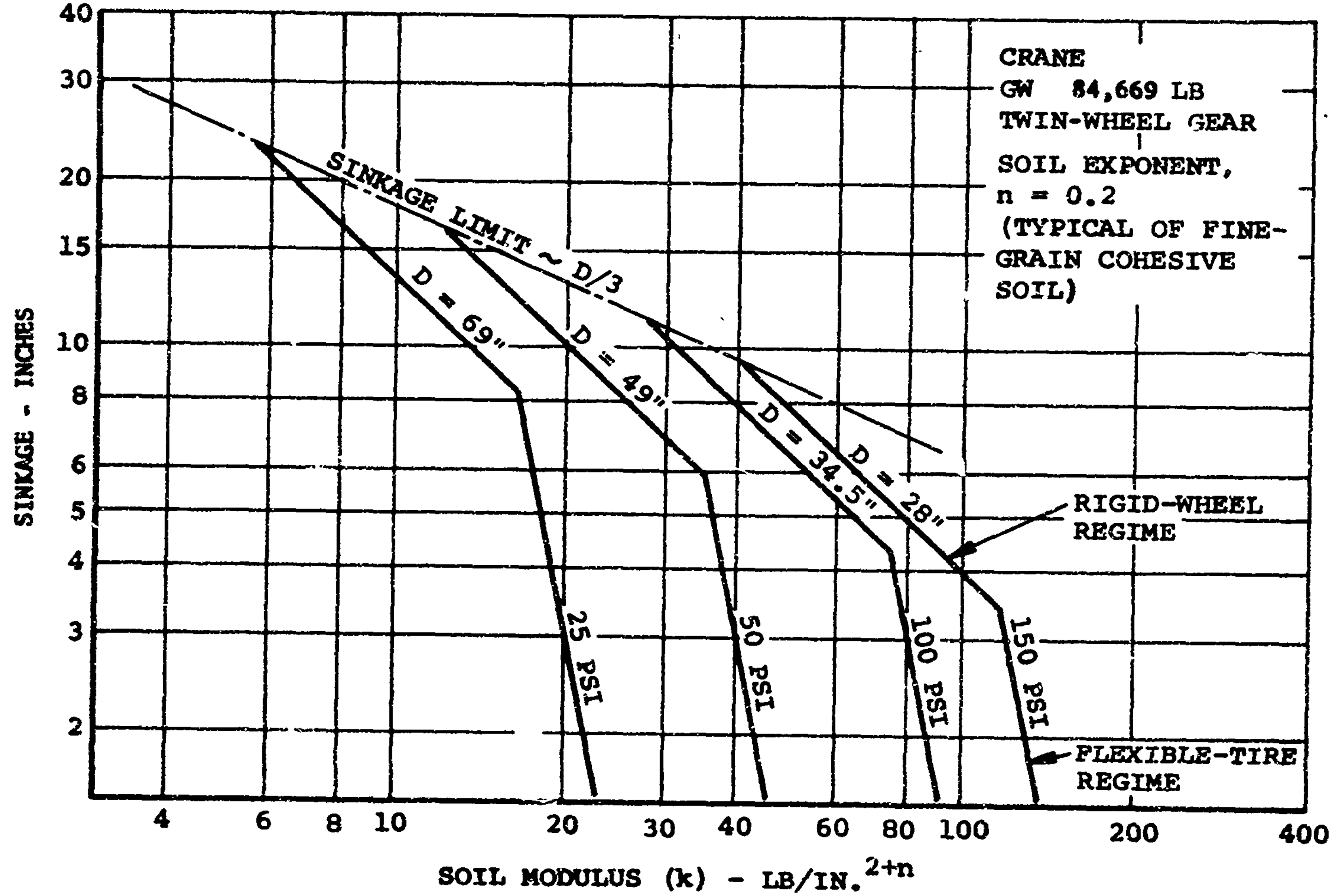


FIGURE 20. TIRE SI??E - TWIN-WHEEL-GEAR CRANE (84,669 LB)

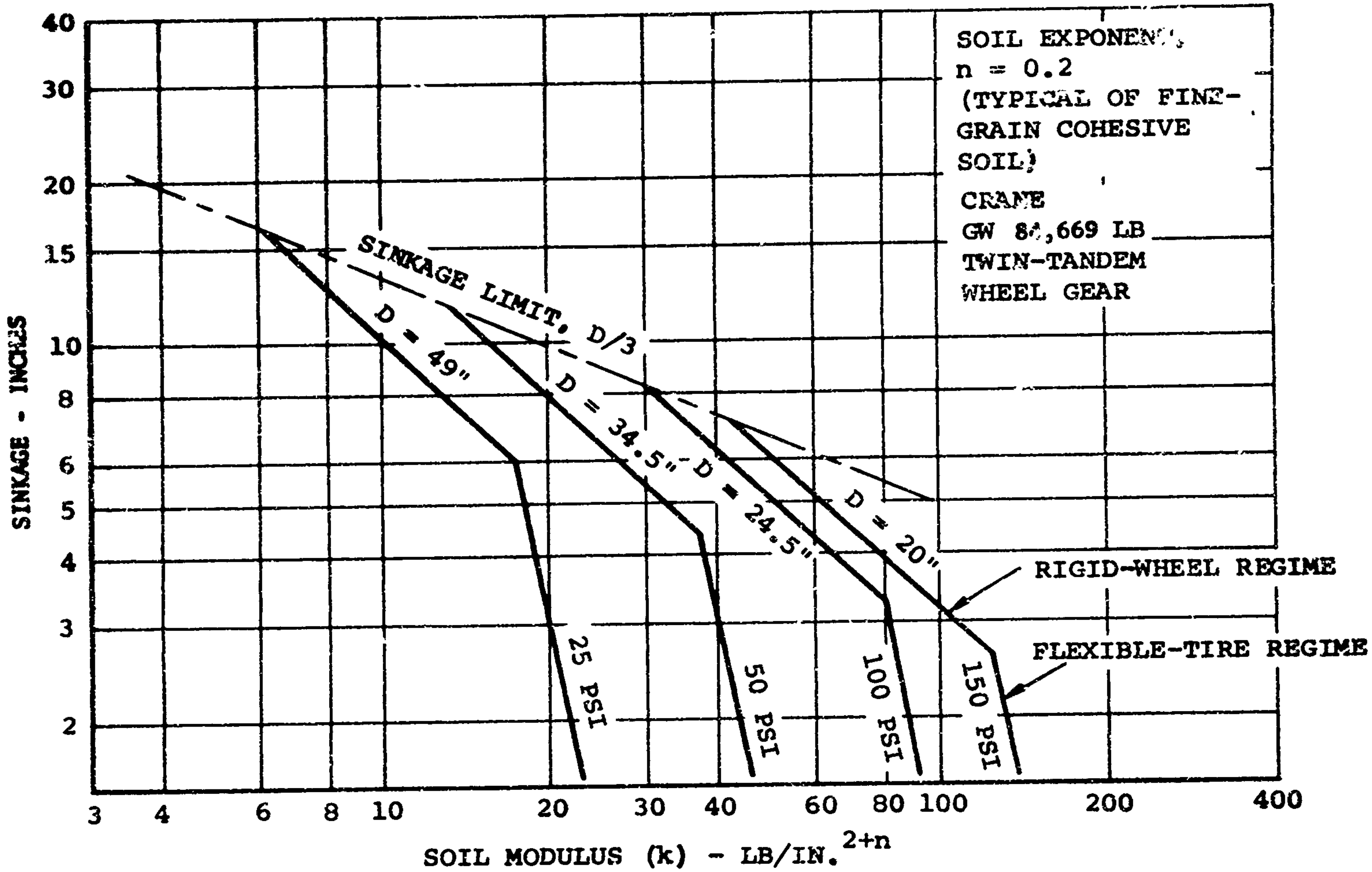


FIGURE 21. TIRE SINKAGE - TWIN-TANDEM-GEAR CRANE (84,669 LB)

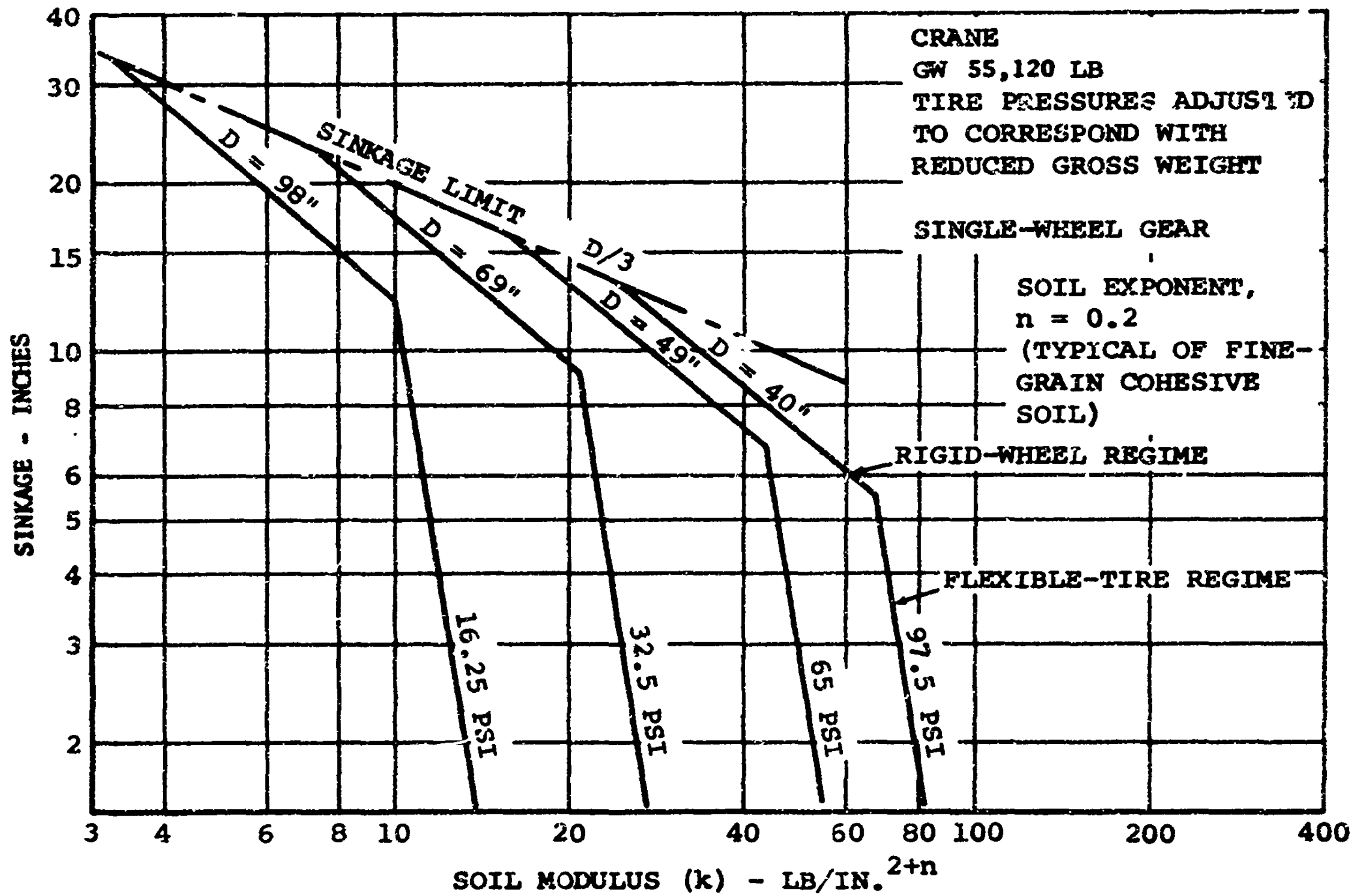


FIGURE 22. TIRE SINKAGE - SINGLE-WHEEL-GEAR CRANE (55,120 LB)

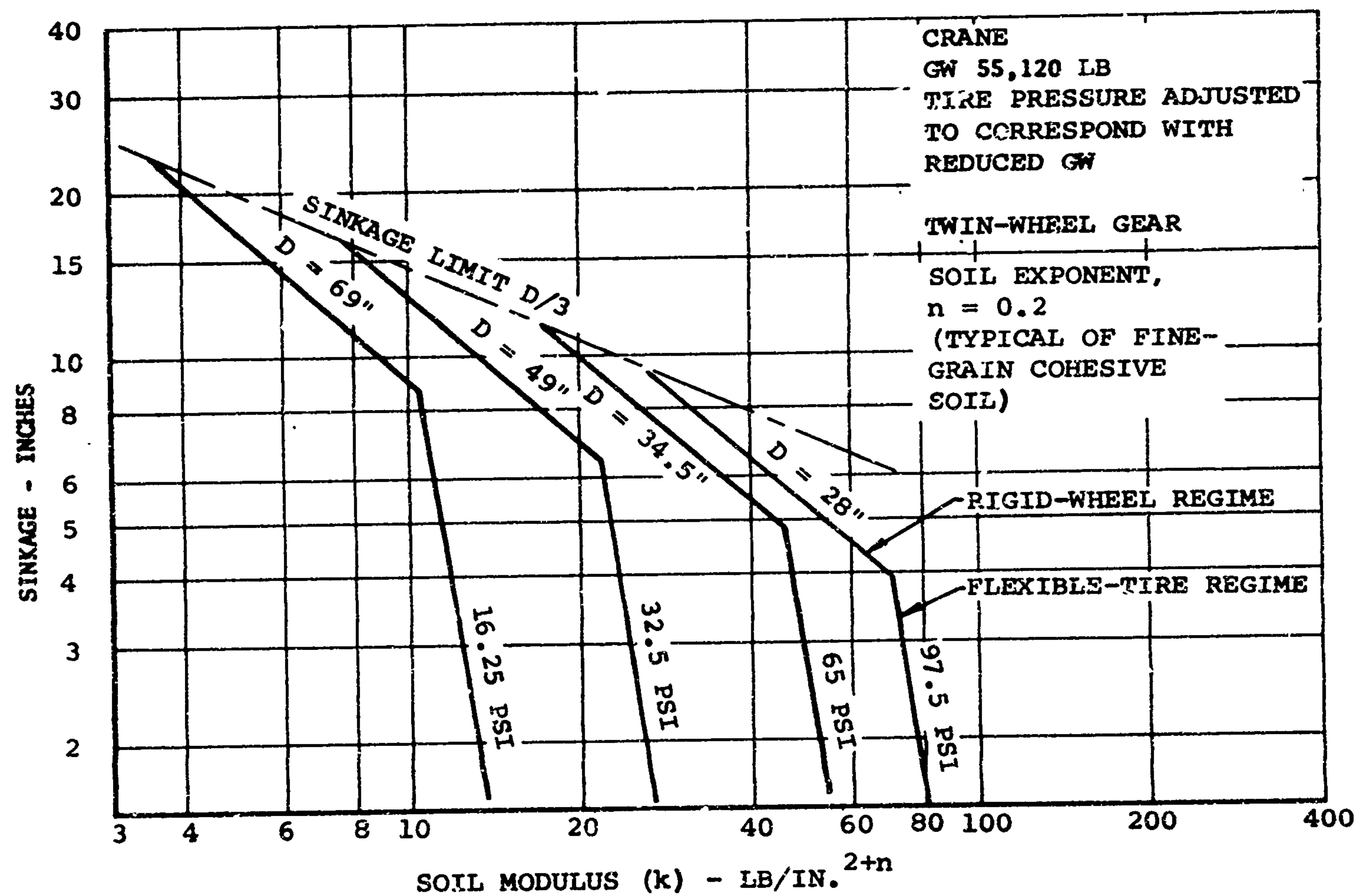


FIGURE 23. TIRE SINKAGE - TWIN-WHEEL-GEAR CRANE (55,120 LB)

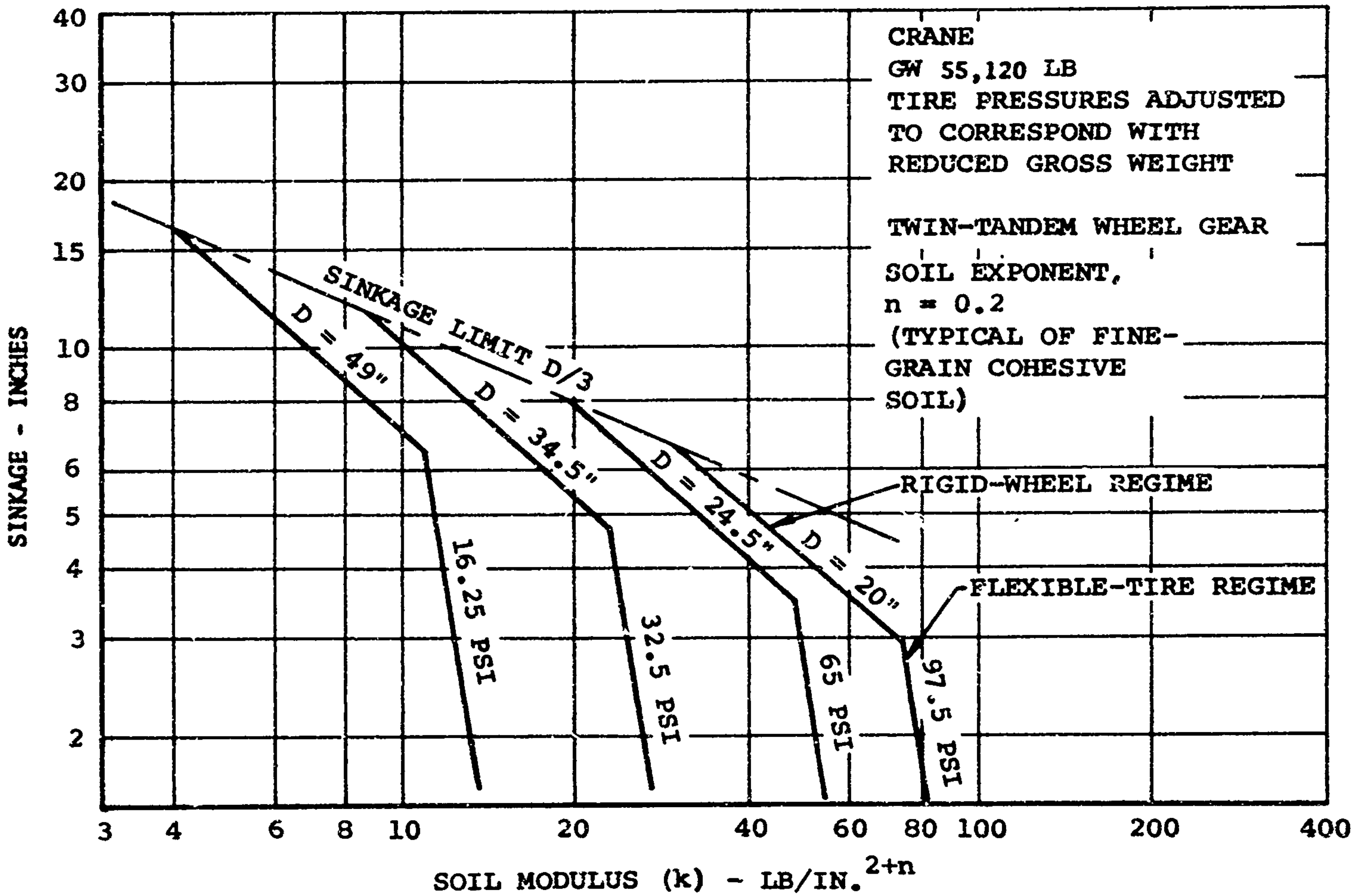


FIGURE 24. TIRE SINKAGE - TWIN-TANDEM-GEAR CRANE (55,120 LB)

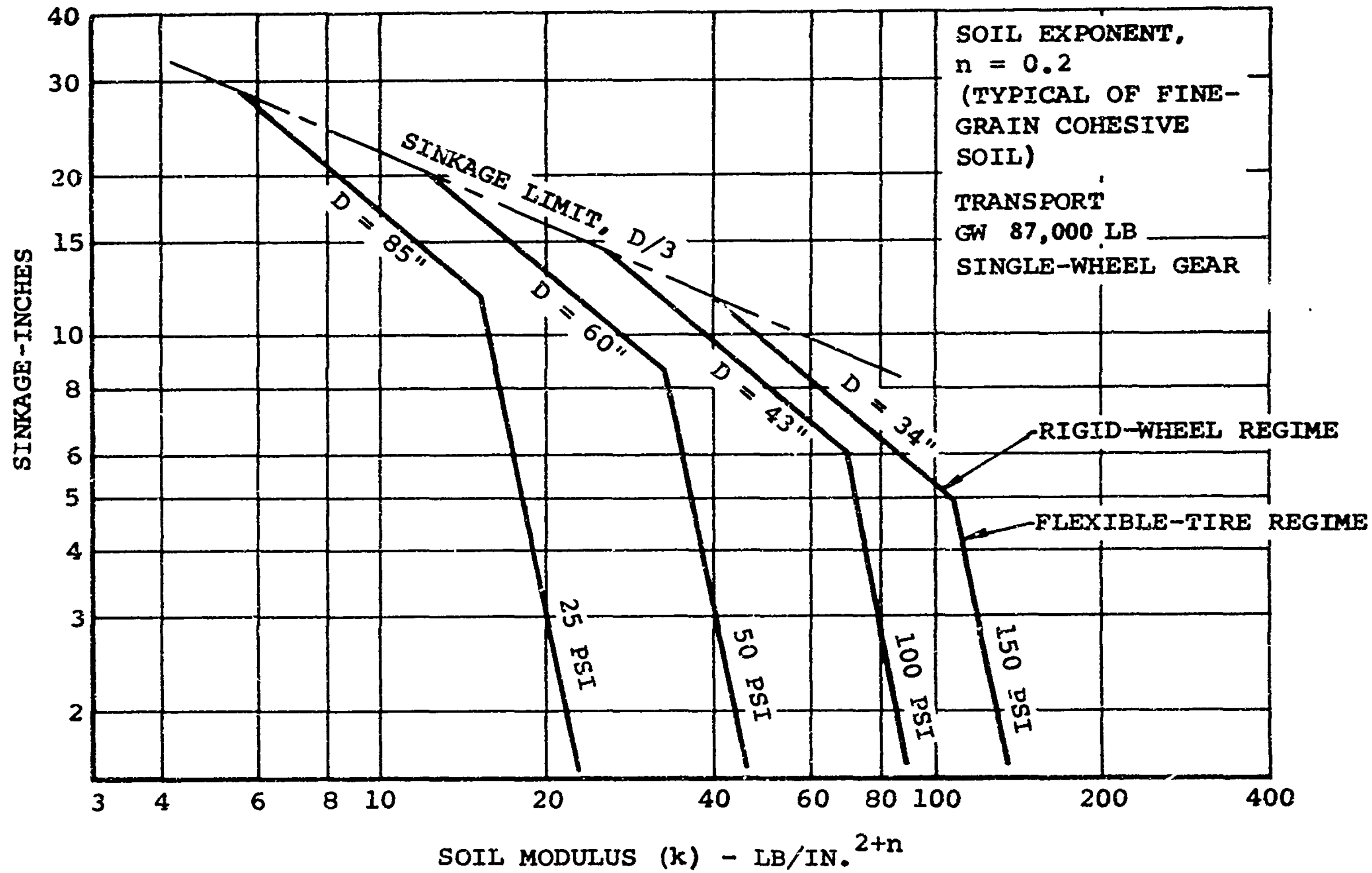


FIGURE 25. TIRE SINKAGE - SINGLE-WHEEL-GEAR TRANSPORT (87,000 LB)

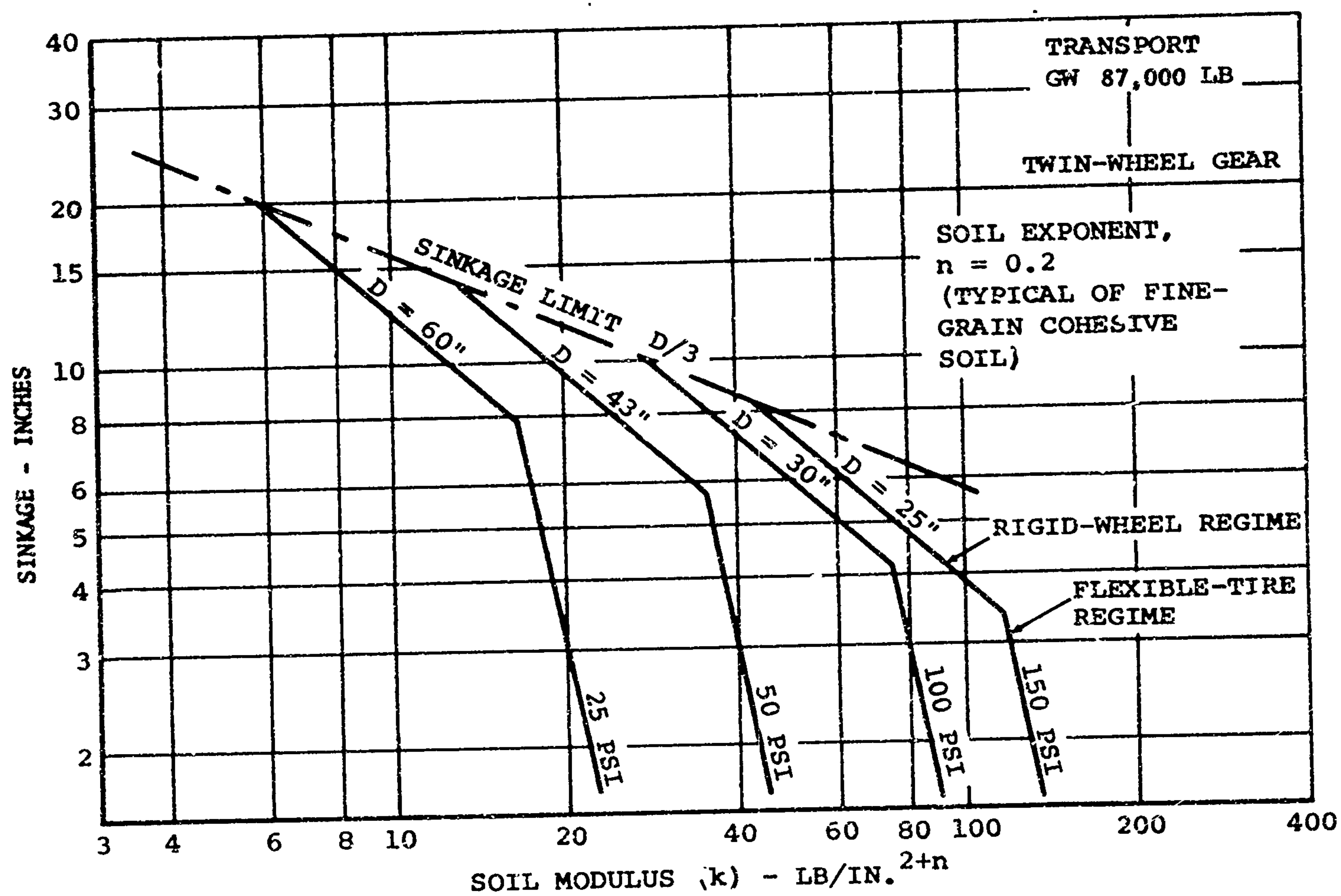


FIGURE 26. TIRE SINKAGE - TWIN-WHEEL-GEAR TRANSPORT (87,000 LB)

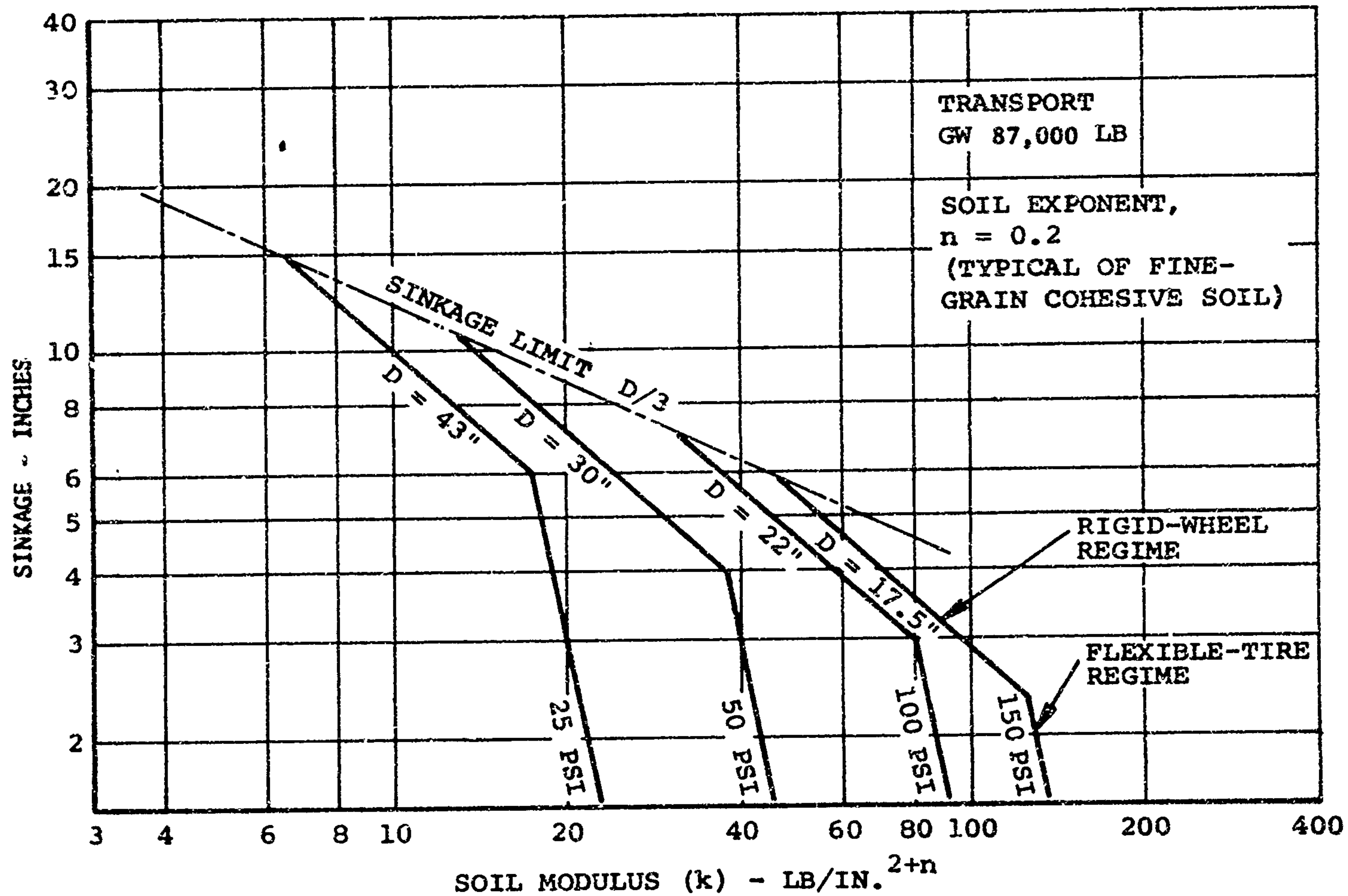


FIGURE 27. TIRE SINKAGE - TWIN-TANDEM-GEAR TRANSPORT (87,000 LB)

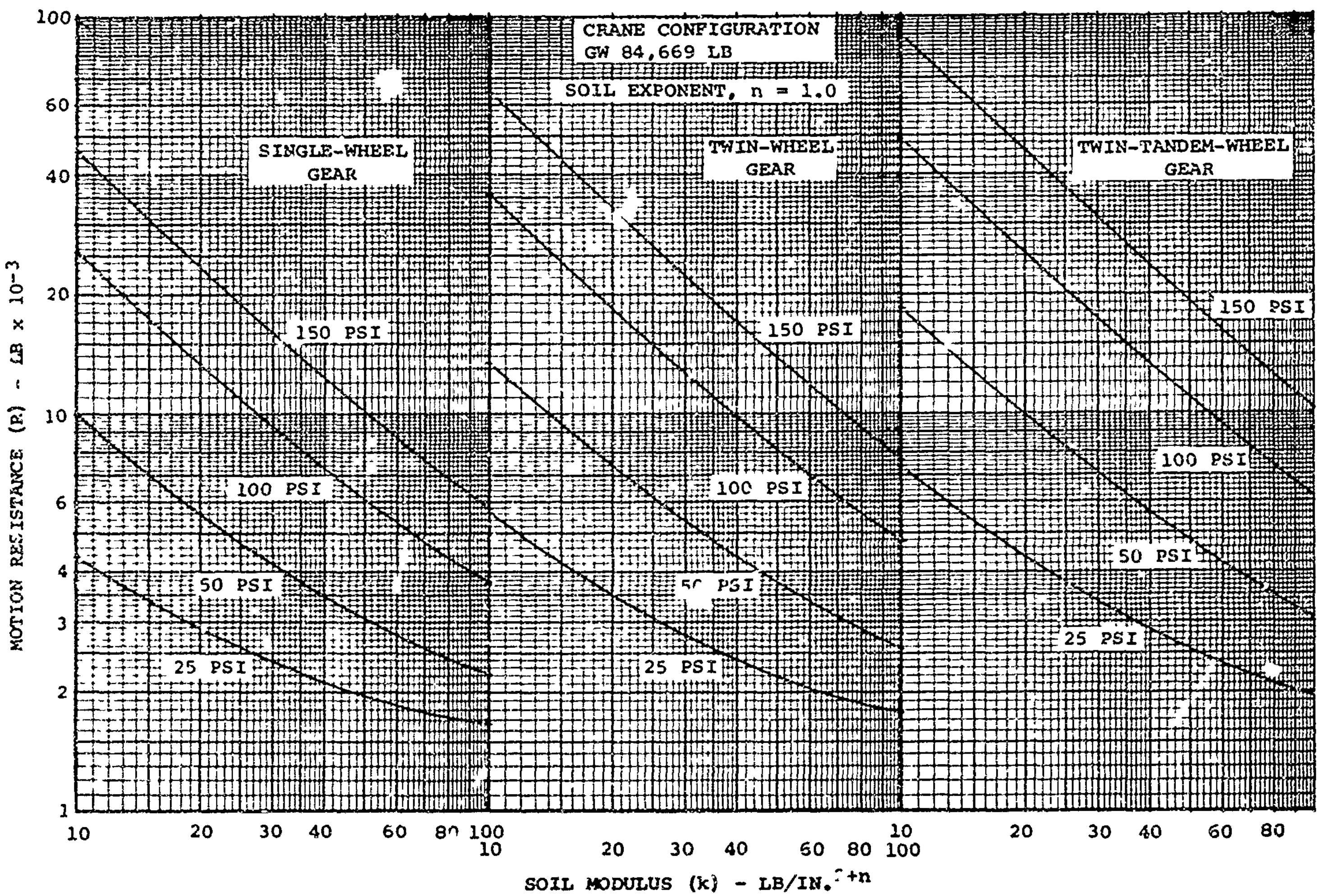


FIGURE 28. MOTION RESISTANCE IN SOFT SOIL - CRANE, GW 84,669 LB

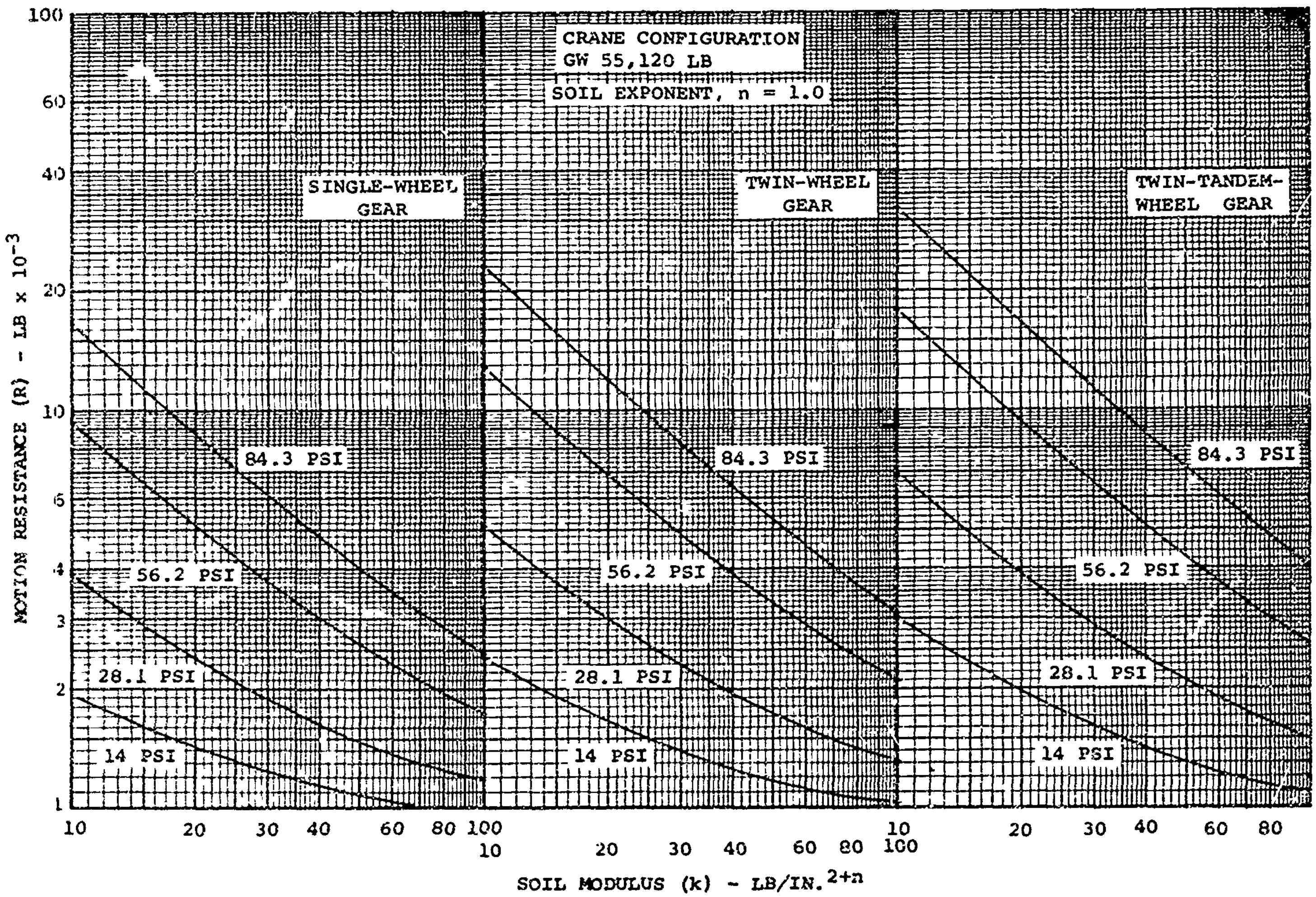


FIGURE 29. MOTION RESISTANCE IN SOFT SOIL - CRANE, GW 55,120 LB

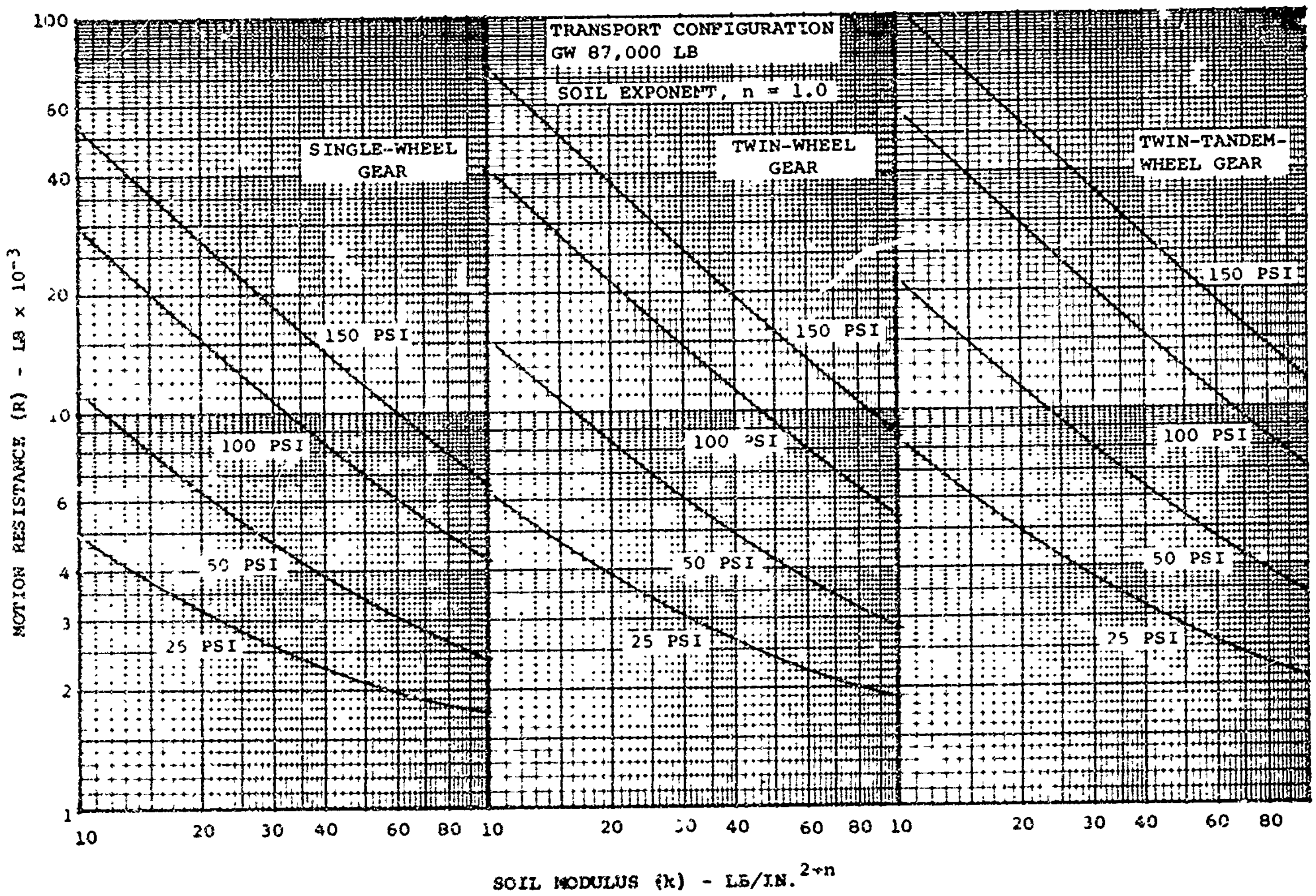


FIGURE 30. MOTION RESISTANCE IN SOFT SOIL - TRANSPORT, GW 87,000 LB

(U) RECOMMENDATIONS

As a result of this study it is recommended that:

1. The flotation criteria for the Heavy Lift Helicopter be based on the provision of sufficient landing gear flotation to permit the following operations:

   a. Zone of Interior - unlimited use of heavy-, medium- and light-load airfields.

   b. Theater of Operations - 200 coverages on a support-area field or 40 coverages on a forward-area field.

   c. Safe landing and lift-off from unprepared soil with a Cone Index of 30.

   A field-installed high-flotation landing gear kit will be provided to permit safe operations in soil with a Cone Index of 10. At the option of the procuring agency, this requirement may be replaced by one specifying snow skis also suitable for operation on unprepared terrain.

2. Analysis be made of the total utilization of Theater of Operations airfields in order to establish the credibility of the coverage rates defined in paragraph 1 above.

3. A pass-to-coverage ratio for helicopter operations be established for various landing gear arrangements.

4. A method of analysis of flotation in unprepared soft soil be developed based on safe lift-off criteria. If possible, this method should be presented in a form similar to the Corps of Engineers nomograph for operation from unsurfaced soil.

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1. ORIGINATING ACTIVITY (Corporate author) Vertol Division The Boeing Company Morton, Pennsylvania	2a. REPORT SECURITY CLASSIFICATION Confidential 2b. GROUP Group 4

3. REPORT TITLE

Investigation of Landing Gear Flotation Criteria for the Heavy Lift Helicopter (U)

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Technical Report

5. AUTHOR(S) (Last name, first name, initial)

Harding, David G.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
August 1967	96	16

8a. CONTRACT OR GRANT NO. DA 44-177-AMC-455(T) b. PROJECT NO Task 1F121401A14184 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) USAAVLABS Technical Report 67-42 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) D8-0547; C67-1654

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13. ABSTRACT

Mission analyses were performed for a draft-QMR-type Heavy Lift Helicopter operating in Southeast Asia, Western Europe, and the Continental United States in order to establish landing gear requirements. The results of these analyses indicate that both crane and transport configurations are equally capable for the majority of missions from landing gear flotation considerations; however, the helicopter configured solely for external loads has an advantage, since tire pressures may be reduced to correspond to the basic weight condition.

The coverage rates recommended by the Corps of Engineers were used in the flotation analysis to indicate corresponding landing gear requirements.

DD FORM 1 JAN 64 1473

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Heavy Lift Helicopter						
Landing Gear Design						
Flotation						

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